ACTA RADIOLOGICA

SUPPLEMENTUM 238

CIRCULATION IN TRAUMATIC AMPUTATION STUMPS

AN ANGIOGRAPHICAL AND PHYSIOLOGICAL INVESTIGATION

BY

UNO ERIKSON

Uppsala

STOCKHOLM 1965

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CIRCULATION IN TRAUMATIC AMPUTATION STUMPS

AN ANGIOGRAPHICAL AND PHYSIOLOGICAL INVESTIGATION

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STOCKHOLM 1965

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CHAPTER I

Introduction

Increasing attention is paid nowadays to the rehabilitation of handicapped persons. Patients with leg amputations comprise a fairly small number of these persons and as a rule are able to return to some sort of work after the amputation if they have not reached a pensionable age. The socio-medical position of these patients has been treated by Hanson (1964), among others, and their psychiatric status by Cronholm (1951). A number of leg amputees have post-amputation symptoms which prevent their rehabilitation, for example, pain in the stump and/or the phantom limb, often of great intensity. Also, the skin of the stumps is often red and is easily subject to infection and friction sores. The aetiology of these symptoms is still being discussed. A number of authors claim that the cause of the stump pains is to be found in the central nervous system, while others consider that these pains have their origin in the tissues of the stump itself, possibly due to changes in blood flow. This latter viewpoint has not been based on any comprehensive investigations up to the present time, and it was therefore considered of interest to study the vascular anatomy and certain physiological functions of the amputation stump vessels, and to attempt to correlate objectively measured findings to symptoms in the form of pain, ulcers and tenderness in the stump.

CHAPTER II

Angiography of Amputated Legs

In discussions concerning pathological conditions in amputations stumps, especially pain, some attention has been paid to their blood flow and vascular anatomy. Leriche (1920) considered that spasm and obliteration could play a pathogenetic role in amputation stump pains, and he recommended arteriectomy and sympathectomy in patients with such symptoms. The same author later (1949) pointed out the need for more systematic arteriographical investigations, and gave a brief report of three patients on whom arteriography had been performed. One of these patients, who had undergone amputation because of gangrene following scarlet fever, had repeated symptoms of atrophic disturbances in the stump, and arteriography showed conditions such as are found with total occlusion of the superficial femoral artery. A further arteriography carried out after sympathectomy, however, showed free passage in the artery, which Leriche interpreted as a sign that a spasm had been present at the first investigation, simulating total occlusion. He considered on these grounds that in a number of amputees the circulation was reduced. The other two patients reported had ulcers, oedema and pain in their amputation stumps, and in these cases arteriography revealed profuse vascularization with tortuous arteries and signs of arteriovenous communications, judged by Leriche as newly formed. On the basis of these three patients Leriche classified amputation cases into two groups, one with a poor circulation (hypocirculation) and one with profuse circulation (hypercirculation). Erikson (1961) and Erikson & Hulth (1962) made arteriographical studies on small groups with traumatic leg amputations, and found a tendency towards a correlation between profuse vascularization in the amputation stumps and pain and tenderness in these stumps.

Hasse, Rau & Schoop (1959) described an arteriography in a below-knee amputee, but only discussed the reasons for caliber decrease in the superficial femoral artery, the popliteal artery and the three lower leg arteries.

No comprehensive report on the arteriographical picture in amputated legs appears to have been published up to the present time.

The author has therefore considered it of interest to evaluate, in a large series of cases, the variations in vascular richness in the amputation stump and also the appearance of both the small and the main arteries.

Material of Patients

Altogether 102 patients are included in this angiographic investigation. All patients examined were referred to the Roentgen Department of the University Hospital, Uppsala during the period from August 1960 to August 1963. (The patients came from the whole of Sweden, a large number being referred via the Insurance Company "Folksam", and a small number via doctors in our own receiving area.) Only patients amputated as a result of trauma or those comparative with them as regards the absence of general disease, were included. One patient had mitral disease and another a defect of the atrial septum, but none of the patients had signs of peripheral arterial disease. Routine blood tests [sedimentation rate, hemoglobin concentration] showed normal conditions, and apart from disabilities directly connected with the amputation these patients were fully capable of work. No other form of selection was made, all patients who were able to undergo a complete investigation with the present methods being included in the study. In four

	Observation time, years	Type of amputation	Age at time of investigation											
			10 - 19 years		20 - 29 years		30 - 39 years		40 - 49 years		50 - 59 years		60 - 69 years	
			M	F	M	F	M	F	M	F	M	F	M	F
Unilateral amputation	0 - 5	AK	1		6		6		1		5		2	
		BK	2	1	3		6		8		2		3	
	6 - 10	AK	1	1	3		1		5	1	1			
		BK	1		3				1		3	1	2	
	11 - 15	AK					1		2		1			1
		BK			1		1			1				
	16 - 20	AK												
		BK									2	2	1	
	21 - 25	AK												1
		BK							1					
	26 - 30	AK												
		BK							1					
	31 - 35	AK												
		BK												
	36 - 40	AK											1	
		BK												
	45 - 49	AK									1		1	
		BK												
Bilateral amputation	0 - 5	AK			1									
		BK			1						1			
	6 - 10	AK					1							
		BK									1			
	11 - 15	AK												
		BK	1						1					
	16 - 20	AK												
		BK									1			
	41 - 45	AK												
		BK											1	

Table 1. The table shows the distribution of above-knee (AK) and below-knee (BK) amputees, both unilateral and bilateral, in relation to observation time and age of amputees at time of investigation.
M = male, F = female patients.
n = No. of patients

Age at time of amputation years	Above knee amputees						Below knee amputees					
	Unilateral				Bilateral		Unilateral				Bilateral	
	male		female		male		male		female		male	
	n	mean age	n	mean age	n	mean age	n	mean age	n	mean age	n	mean age
0 - 9	2	6,5	1	8			1	6			1	2
10 - 19	3	17					3	14	1	17		
20 - 29	10	23			2	26	10	25			3	23
30 - 39	14	35	2	38	1	36	10	36	2	33		
40 - 49	3	44	1	47			13	45	2	44	1	49
50 - 59	5	52					2	55			1	50
60 - 69	1	66					3	63				
0 - 69	38		4		3		42		5		6	

Table 2. Distribution of amputees according to age at amputation.

	Reason for amputation	Age at time of amputation															
		0 - 9 years		10-19 years		20-29 years		30-39 years		40-49 years		50-59 years		60-69 years		Total	
		M	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F
Unilateral amputation	Trauma	2		3		9		12	1	3		5		1		35	1
	Infection					1										1	
	Tumour		1					2	1		1					2	3
Bilateral amputation	Trauma					2		1								3	
Total No.		2	1	3		12		15	2	3	1	5		1		41	4

Table 3 A. Distribution of above-knee amputees, according to age at amputation and reason for amputation. (M = male, F = female patients).

	Reason for amputation	Age at time of amputation															
		0 - 9 years		10-19 years		20-29 years		30-39 years		40-49 years		50-59 years		60-69 years		Total	
		M	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F
Unilateral amputation	Trauma	1		3	1	11		8	1	9		2		2		36	2
	Infection							2	1	3	2					5	3
	Tumour													1		1	
Bilateral amputation	Trauma	1				3				1		1				6	
Total No.		2		3	1	14		10	2	14	2	3		3		48	5

Table 3 B. Distribution of below-knee amputees, according to age at amputation and reason for amputation. (M = male, F = female patients).

patients, all of whom were above-knee amputees with short leg stumps, the contrast injection was unsuccessful. These cases were therefore excluded. Tables 1, 2 and 3 show the ages of the patients at the time of amputation, the ages at the time of investigation, the number of years that had elapsed between amputation and investigation ("observation time") and the relationship between age at amputation and the observation time up to the time of investigation. The cause of amputation and the sex of the patients are given in Table 3. Other clinical data such as post-operative symptoms and their duration, and reamputations, are reported in chapter 6.

Table 1 shows that at the time of investigation about half of the amputees were of ages 40–59 years, while 8 patients were less than 19 years old and 13 patients were of ages 60–69 years. The observation period, which in a number of patients was relatively long, increased with increasing age. For example one 68-year old man had an above-knee amputation at the age of 19 years, one 53-year old man had a similar amputation at the age of 7 years, and one 67-year old man had bilateral below-knee amputations at the age of 23 years.

The majority of the patients underwent amputation between the ages of 20 and 39 years (Table 2). Only 5 patients were less than 9 years old at the time of amputation, and only 4 patients were over 60 years old. Nine of the patients were women and 89 men.

The causes of amputation are shown in Table 3, where it may be seen that the most common was trauma caused by an accident; 83 patients had been amputated after accidents, and 9 after infections. These 9 patients included 7 who after an accident with trauma sustained secondary infection which was the determining reason for amputation; in 2 patients the reason was tubercular osteomyelitis. In 6 cases malignant tumour was the cause of amputation. In all of the 9 patients with bilateral amputations these were the result of trauma.

Methods

Roentgen equipment. All of the patients were investigated in the same roentgen laboratory, with the same equipment (Elema-Schönander Ltd., Solna, Skantic model). The focus-film distance was 125 cm, and serial exposure was made by means of a film changer with automatic injector as according to Gidlund (1956). Frontal pictures were obtained using vertical ray directions on recumbent patients.

Procedure. The patient rested on the examination table for at least 30 minutes before the investigation while preparations were being made. The room temperature was about 23° C and the patient was covered with blankets

and felt comfortably warm in both the body and legs. Test pictures for the choice of a suitable exposure were taken during the preparation period.

The femoral artery on the amputated or intact side was punctured under local anaesthesia immediately distal to the inguinal ligament. Using the technique of Lindbom (1950) the injection needle, and therefore the contrast injection, was directed against the blood flow. The needle was connected to the syringe with a polythene tube, and the injection was given by hand. This technique was used in 91 investigations. In 27 investigations a different technique was used; a polythene cathene with an external diameter of 2.08 mm and an internal diameter of 1.57 mm was introduced into the femoral artery against the blood flow as according to the Seldinger principle, so that the tip of the catheter was situated about 7–8 cm proximal to the puncture site. The contrast was then injected by hand; in 8 cases by means of an automatic Gidlund pressure syringe. In 4 of these latter cases the tip of the catheter was situated above the bifurcation of the aorta and was introduced through the artery of the intact leg. In all other cases the contrast medium to the stump was injected on the amputated side.

Urografin 60 % (Schering, Berlin) was used for all the investigations. In the amputated leg 15–20 ml of this substance was injected into the femoral artery, and in the intact leg 20–25 ml.

The frequency in the arteriographies was 1 frame/sec for 15–25 sec, exposure time per picture less than 0.023 sec, at 60–90 kV and 250–400 mA. When the needle and catheter were removed the puncture site was compressed manually for 10 minutes in order to avoid a haematoma, and a local pressure bandage was then applied. After the investigation the patient rested under supervision for at least one hour, lying on a wooden board. The patients were instructed to inform the examiner if there was any discomfort following the investigation.

Complications. In 3 above-knee amputees, with short leg stumps, the contrast injection was unsuccessful and part of the contrast medium was injected extravasally; this caused no discomfort, however, or signs of circulatory disturbance. In one female above-knee amputee a haematoma occurred in connection with the arterial puncture, and the investigation was therefore discontinued. These 4 patients have not been included in this report. In none of the other patients did any haematoma, infection or circulatory disturbance occur. In some of the above-knee amputees, however, the puncture site was irritated by the socket of the prosthesis.

Method Control

In order to determine whether the different techniques of injecting the contrast medium i. e. via a needle or catheter, had any effect on the results,

in 7 patients contrast was injected by hand via both needle and catheter. Both methods gave the same degree of filling of the whole arterial vascular network. There was also good agreement in 4 other patients on comparison between arteriographies in which the contrast was injected by hand via a needle and those in which it was introduced by means of a pressure syringe through a catheter. In one further case the contrast was injected via a catheter both by hand and by means of a pressure syringe; in this case also the results of the two methods were in agreement. With some reservation for the smallness of the material a comparison between the arteriographic results in different patients therefore seems possible in spite of the somewhat varied techniques used.

The investigations performed with both vertical and horizontal ray directions in 3 patients showed no signs of "sedimentation" of the contrast medium to the declivitous parts of the leg, or layer formation. It cannot be precluded, however, that with a very low blood flow sedimentation may occur (Kjellberg 1943).

There is always uncertainty, however, that the contrast medium passes through all the vascular regions. This problem is present in all conventionally performed arteriographies, and is not taken into account in comparing cases in the present study.

The constant frequency of 1 frame/sec was chosen because of the practical difficulties in determining the exact frequency of exposure on shifting from one speed to another during one and the same arteriography. Theoretically it would seem desirable to have a higher frequency in the arterial phase and a lower in the venous phase. This, however, would probably not have provided more anatomical information.

The commercial apparatus used for recording the exposure frequency (Mingograf 42, Elema—Schönander AB, Solna) was not available until the last year of investigation.

Results

I. *Arterial system*

The arteriographies were evaluated from the following aspects:

1. Degree of arterial richness in the amputation stump.
2. Incidence of spiralled arteries in the amputation stump.
3. Exostosis and its relationship to the arteries in the amputation stump.
4. Occurrence of arteriovenous communications.

5. Occurrence of wall changes of arteriosclerotic-like appearance in the main arteries.
6. Occurrence of the "standing-wave" phenomenon.

1. *Degree of arterial richness in the stump.* For evaluating the arterial richness in the amputation stump, the material was divided into three groups. Group 1 consisted of patients whose amputation stumps exhibited the same richness of arteries as was found at the corresponding level of the intact leg, group 2 consisted of patients with comparatively moderately increased arterial richness, and group 3 patients with comparatively markedly increased arterial richness in the stump. The vascular richness in the above-knee amputees was evaluated in the distal 20 cm of the amputation stump, and in the below-knee amputees in the entire stump distal to the knee joint.

In 24 of the above-knee stumps an arterial richness of grade 1 was observed, in 17 a richness of grade 2 and in 7 a richness of grade 3. In 28 of the below-knee stumps an arterial richness of grade 1 was observed, in 18 a richness of grade 2 and in 13 a richness of grade 3 (Tables 4 and 5).

Figs. 1–8 show arteriographies illustrating the different groups.

2. *Incidence of spiralled arteries in stump.* In many amputation stumps, arteries which had a tortuous course and which were not amongst the types occurring in the intact leg were seen. These arteries which resembled spirals will be referred to in the following as "spiralled arteries". With respect to

Spiralled arteries group	Richness of arteries			Total
	1	2	3	
1	23	2		25
2	5	14		19
3		2	13	15
Total	28	18	13	59

Table 4. Distribution of below-knee amputees according to richness of arteries and the occurrence of spiralled arteries.

Spiralled arteries group	Richness of arteries			Total
	1	2	3	
1	21	6	0	27
2	3	10	1	14
3	0	1	6	7
Total	24	17	7	48

Table 5. Distribution of above-knee amputees according to richness of arteries and the occurrence of spiralled arteries.

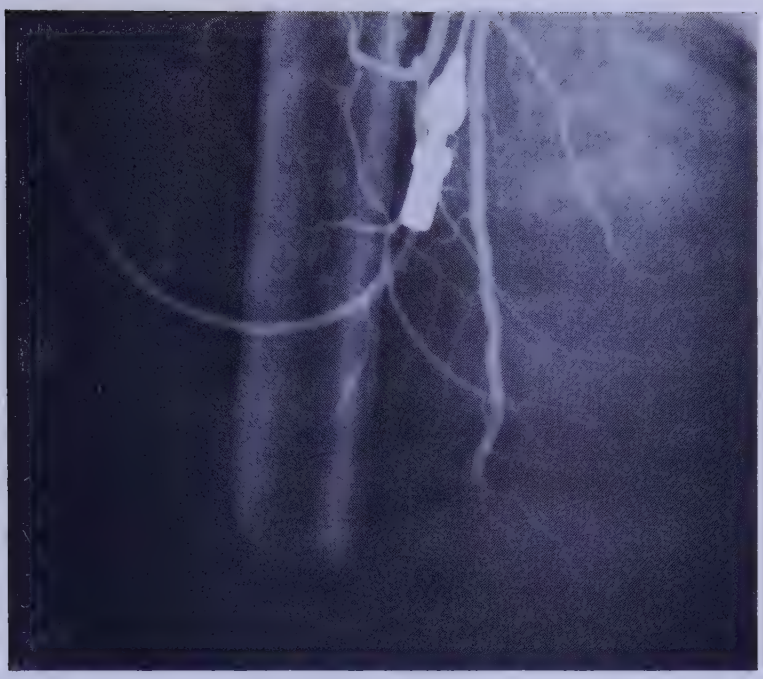

Fig. 1. (33063/61) Female amputee, 61 years old. The patient was amputated 14 years ago because of a tumour. Group 1 with respect to tortuosity and richness of arteries.

the occurrence of these arteries in the amputation stump the material is divided into three groups. In group 1 there are no spiralled arteries, in group 2 there is a moderate occurrence, and in group 3 they occur abundantly (see Figs. 1–8). Among the above-knee amputees 27 stumps had no spiralled arteries, 14 had a moderate occurrence and 7 had an abundance of such arteries. In the corresponding groups of the below-knee amputees there were 25, 19 and 15 stumps, respectively (Tables 4 and 5). A high degree of spiralled arteries was found in particular in those amputation stumps which had a markedly increased arterial richness.

The mean age in the above-knee amputees at the time of investigation was approximately the same in the three groups with different frequencies of spiralled arteries. In the below-knee amputees there was a tendency to a higher mean age with higher frequencies of these arteries (Fig. 9).

3. *Spur formations.* Spur-shaped exostoses were observed in both above- and below-knee amputees. The distal branches of the superficial femoral artery, the popliteal artery and in some cases the deep femoral artery were in certain cases directed towards the region in the vicinity of the bone spur

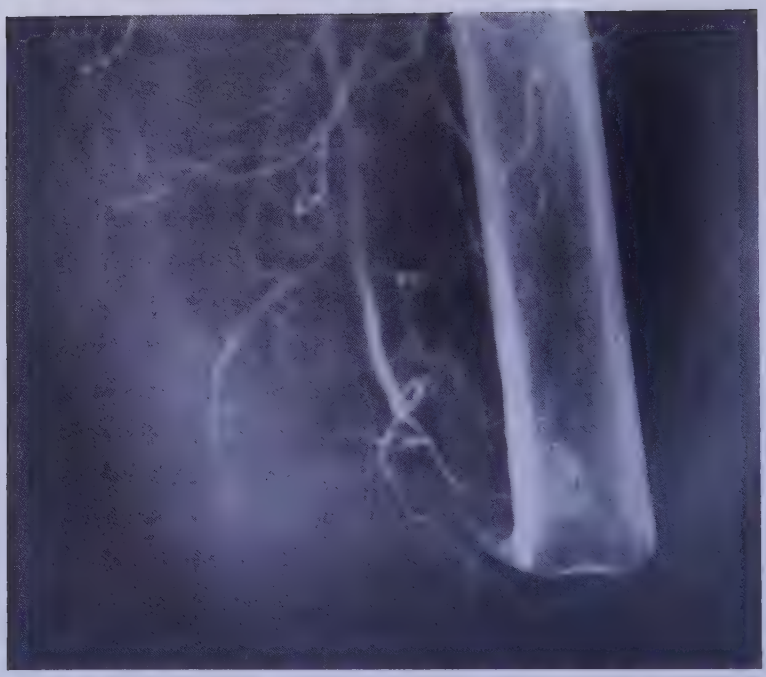

Fig. 2. (32450/61) Male amputee, 53 years old. Amputated because of trauma 8 years ago. Group 2 with respect to tortuosity and group 1 with respect to richness of arteries.

Fig. 3. (23640/60) Male amputee, 55 years old. Amputated 4 years ago because of trauma. Group 3 with respect to tortuosity and group 2 with respect to richness of arteries.

Fig. 4. (16786/61) Male amputee. 48 years old. Amputated 7 years ago because of trauma. Group 3 with respect to tortuosity and richness of arteries.

and could be clearly distinguished in their courses from the other branches in the amputation stump (Figs. 10, 11 and 13). In some cases where there was no or only a tendency to a bone spur, the vascular network showed a similar arrangement towards the distal bone end in the femur, tibia and sometimes the fibula (Fig.12). Table 6 shows the frequency of exostoses in below- and above-knee amputees.

Among the *below-knee amputees* 32 stumps had no exostosis, while in 24 this was clearly observed and in 3 stumps there was an incipient exostosis. In 4 of the 32 patients without an exostosis the arterial network could be said to be related to the distal bone end, and in 10 of the 24 with an exostosis the relationship of the arterial network to the exostosis was distinct. In the 3 patients with an incipient exostosis this appeared to be unrelated to the arteries and veins.

Fig. 5. (776/61) Male below-knee amputee, 37 years old. Amputated 10 months ago because of trauma. Group 1 with respect to tortuosity and richness of arteries.

	No spur	Small spur	Marked spur
Number of above knee stumps	20	5	23
Number of above knee stumps with relationship between spur and arterial network	6	3	17
Number of below knee stumps	32	3	24
Number of below knee stumps with relationship between spur and arterial network	4	0	10

Table 6. The table shows the frequency of spurs and their relation to the arterial tree.

Fig. 6. (2224/61) Female below-knee amputee, 17 years old. Amputated 5 months ago. Group 2 with respect to tortuosity and richness of arteries.

Among the *above-knee amputees* 20 stumps had no exostoses. Incipient and distinct exostoses were seen in 5 and 23 patients, respectively. In 6 of the 20 patients without an exostosis the arterial network was directed towards the distal femoral end. In 17 of the 23 stumps with an exostosis on the femur the arterial network was directed towards this, and the same held for 3 stumps of the 5 with an incipient exostosis.

Fig. 7. (34775/60) Male bilateral below-knee amputee, 67 years old. Amputated 44 years ago because of trauma. The figure shows the left leg with group 3 with respect to tortuosity and richness of arteries. The findings in the other leg were almost identical. The abnormal vessels are situated in the fibular part of the stump.

4. *Arteriovenous anastomoses.* When contrast-filling of arteries and adjacent veins is so rapid as to appear simultaneously, this is taken as a sign of arteriovenous anastomosis. Three of the 48 above-knee stumps and 17 of the 59 below-knee stumps fulfilled this criterion (Table 7, Fig. 14).

5. *Wall changes in the superficial femoral artery and popliteal artery.* In both above- and below-knee amputees there were wall changes of an arteriosclerosis-like type (Fig. 15 and 16), with protrusions into the lumen in the main arteries. In 39 *above-knee amputees* (mean age 36 years) no such changes were observed. In 9 patients (mean age 56 years) these changes were present, and in 3 of these cases the superficial femoral artery was completely occluded (in 2 of these 3 this was confirmed at operation). In

Fig. 8. (15639/62) Male below-knee amputee, 51 years old, amputated because of trauma 6 years ago. Group 3 with respect to tortuosity and richness of arteries.

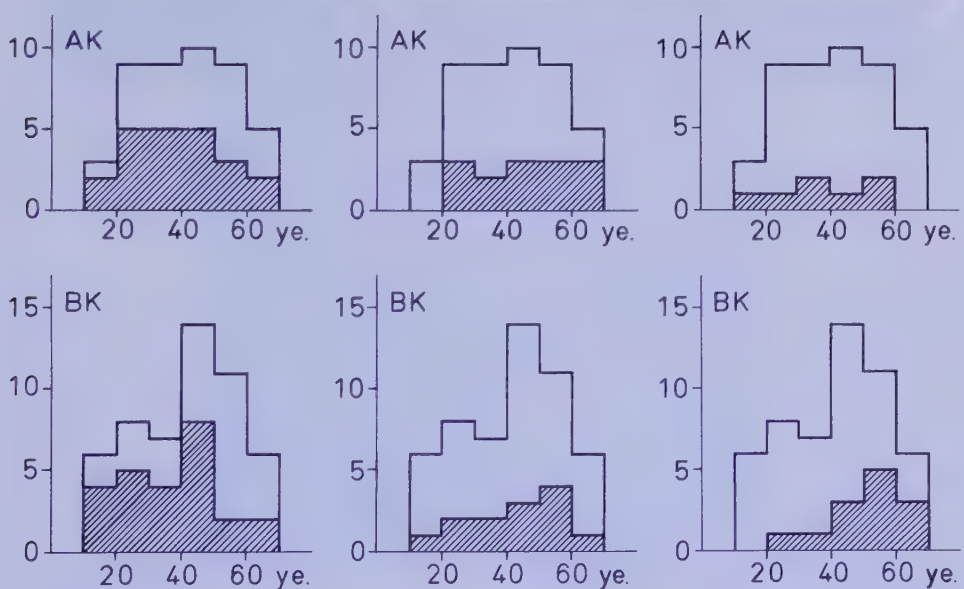

Fig. 9. The figure show the distribution of spiralled arteries in the stumps at different ages at time of investigation, for the three groups.

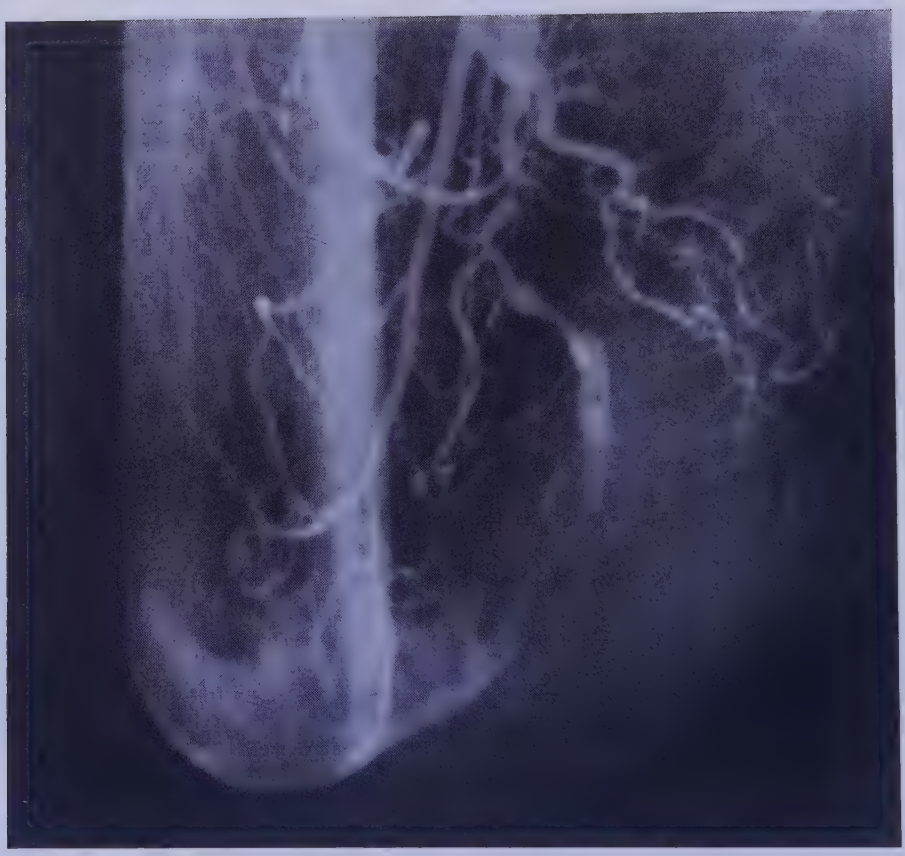

Fig. 10. (36680/61) Male above-knee amputee, 45 years old. Amputated 7 years ago because of trauma. A spur is seen and an artery arising from the superficial femoral artery is directed towards it.

39 *below-knee stumps* (mean age 37 years) no changes were observed in the popliteal artery. In 20 stumps (mean age 55 years) wall changes were present, and in 3 of these cases the popliteal artery was completely occluded (Table 8).

In 7 above-knee amputees with wall changes in the superficial femoral artery of the amputation stump, arteriography of the intact leg was also performed, whereby no changes in the corresponding artery were revealed. In 4 below-knee amputees where the popliteal artery showed changes, arteriography revealed no changes in the intact leg.

In 5 above- and 6 below-knee amputees with no arterial changes in the stump, no changes were observed in the arteries of the intact leg on arteriography.

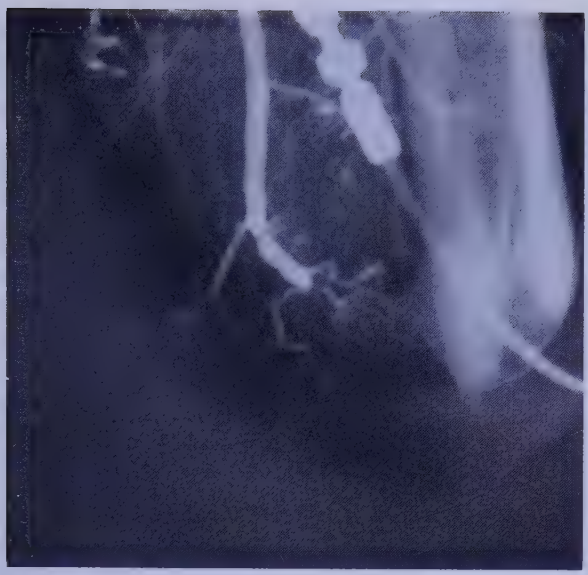

Fig. 11. (33195/61) Male above-knee amputee, 48 years old. Amputated because of trauma 12 years ago. The distal branches from the superficial femoral artery are directed towards the spur.

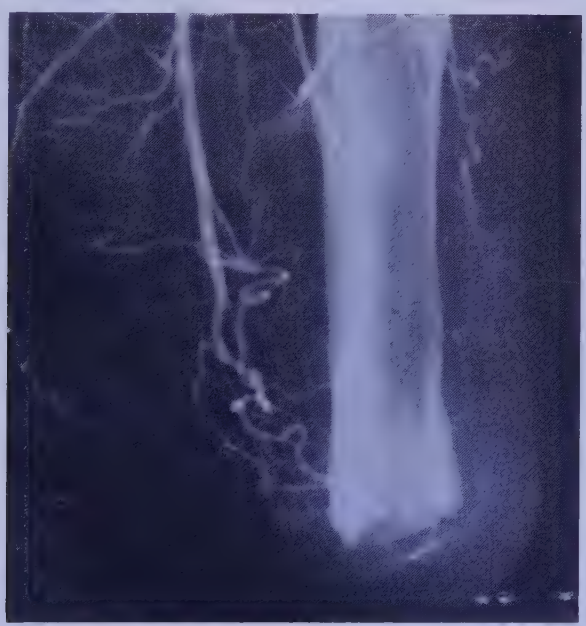

Fig. 12. (10277/61) Male above-knee amputee, 27 years old. Amputated 4 years ago because of trauma. The distal branches of the superficial femoral artery are arranged around the distal part of the femur but no spur is visible.

a

b

a

Fig. 13. (35666/60) Male above-knee amputee, 32 years old. Bilateral amputation 6 years ago because of trauma. Right leg shows spur with related arteries, a, left leg shows no spur and no related arteries (1 second between the 2 pictures of right leg), b.

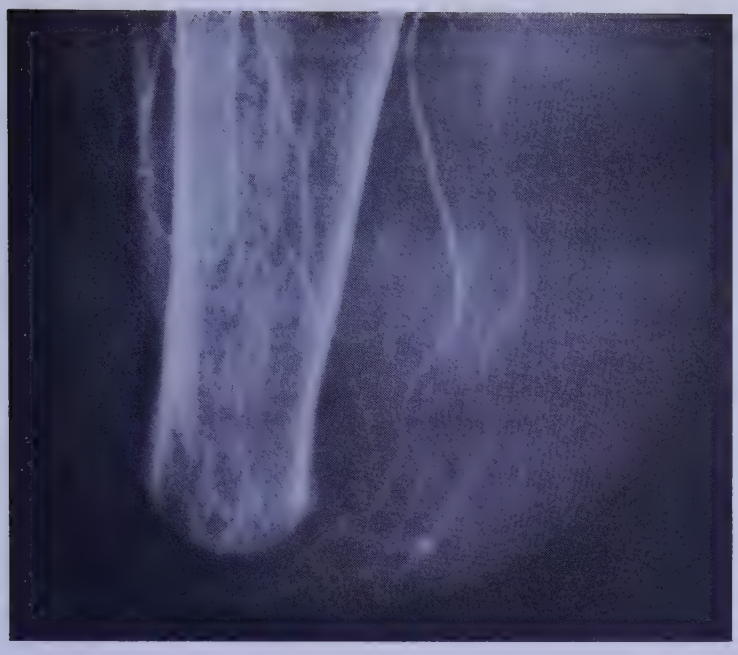

Fig. 14. (9753/61) Male below-knee amputee, 12 years old. Amputated 6 years ago because of trauma. Early and distinct filling of the veins with contrast indicating arteriovenous anastomosis.

Table 7. The table shows the number of arteriovenous anastomoses which is especially high in below-knee amputees. A total of 20 % of all the investigated amputees shows such anastomoses.

Type of amputation	Number of stumps	
	with a-v anastomoses	without a-v anastomoses
Above knee	3	45
Below knee	17	42

6. "*Standing wave*" *phenomenon.* The "standing wave" or arterial wave phenomenon, which has been described by Theander (1961) among others and appears as a band of short contrast columns in the lumen of the artery, was observed relatively frequently in the present series of cases. In 3 above-knee amputees, this was seen in the superficial femoral artery, and in 3 below-knee amputees in the popliteal artery and main branches.

Fig. 15.

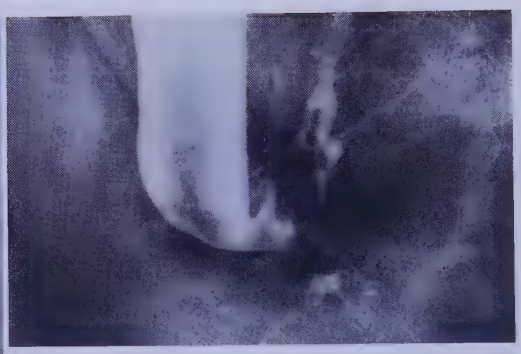

Fig. 16.

Fig. 15. (11780/61) Male above-knee amputee, 61 years old. Amputated 28 years ago because of trauma. The superficial femoral artery shows inward protrusion of the lumen in several places.

Fig. 16. The same patient as in Fig. 15. The contrast medium remained for more than 11 sec. in the distal part of the superficial femoral artery which shows inward protrusion of the lumen in several places.

II. *Venous system*

This investigation was aimed primarily at providing information on the arterial system in the amputation stumps. However in about 50 % of the below-knee and about 60 % of the above-knee amputees contrast filling of the veins was observed. In 5 of the 45 above-knee amputees and 9 of the 53 below-knee amputees this was particularly distinct (Figs. 17 and 18). In the 5 above-knee amputees the arteries were at the same time markedly spiralled (grades 2 and 3), and similarly in the 9 below-knee stumps (grade 3). In 12 out of 20 of the cases with signs of arteriovenous anastomoses there was relatively marked contrast filling of the venous network. The venous pattern sometimes resembled the arterial: for instance during the

Type of amputation		No change of artery wall	Change of artery wall
Above knee	number	39	9
	mean age (years)	36	56
	range	17-66	46-68
Below knee	number	39	20
	mean age (years)	37	55
	range	12-67	25-67

Table 8. The table shows the number of stumps with and without arterial wall changes. The mean age and its range are given for the groups.

venous phase it was seen that particularly wide veins drained relatively small tissue regions, and that the veins often originated in the vicinity of the distal bone end whether or not there was spur formation. The pictures of the venous phase do not, however, give complete information on the anatomy of the veins since it is not known whether the entire venous system was filled with contrast medium.

III. *Arterial system before and after amputation*

In 2 of the above-knee and 1 of the below-knee amputees it was possible to perform femoral arteriography immediately before the amputation and to repeat this investigation a relatively short time after this operation. These cases are illustrated in Figs. 19–22; the investigations showed a tendency to an increase in the lumen of the peripheral arteries and an increase in the arterial network even in the short period since the amputation. This is shown in Figs. 21 and 22 in the region between the tibia and fibula.

In 2 above-knee amputees the arteriographies were repeated on different occasions during the year following the amputation. These patients are described in Figs. 23–29. In 1 of the 2 above-knee amputees (Figs. 23–27) there was some decalcification of the bone in the distal part of the femoral stump post-operatively. Already after 2 weeks the area around the bone stump was relatively rich in both arteries and veins. This finding was still present after 9 months, but by then the arteries had become more tortuous around the femoral stump, and protrusions into the lumen were observed in the distal part of the superficial femoral artery.

The other above-knee amputee is shown in Figs. 28 and 29. At the investigation about three weeks after the amputation a somewhat denser zone was observed around the distal part of the femur. A tortuous artery which

Fig. 17. (32699/61) Male above-knee amputee. 59 years old. Amputated 12 years ago because of trauma. The venous phase is shown. The distal veins are spiralled and the arterial phase was group 3 with respect to spiralled vessels.

Fig. 18. (34775/60) Male below-knee amputee, 67 years old. Bilaterally amputated 44 years ago because of trauma. The distal veins are dilated and spiralled. See also fig. 7.

Fig. 19.

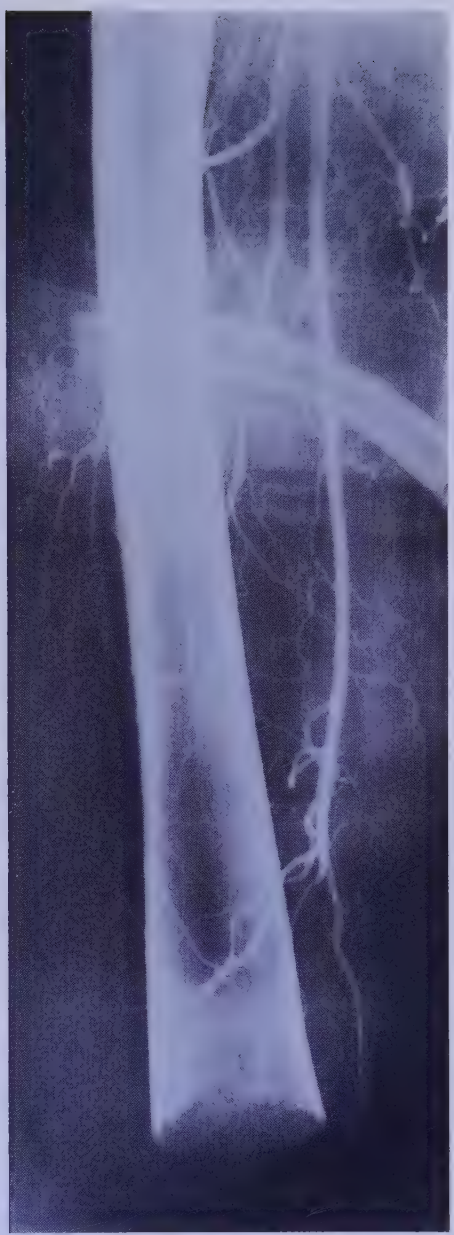

Fig. 20.

Fig. 19. (5651/62) Male patient, 31 years old. There was a complicated trauma distal to the knee. Investigated immediately before the amputation.

Fig. 20. (13344/62) The same patient as in Fig. 19. Investigated 2 months after the amputation. The superficial femoral artery is ligated and its peripheral branches are dilated.

Fig. 21.

Fig. 22

Fig. 21. (33675/60) Male patient, 25 years old, investigated prior to amputation. Previous foot amputation because of trauma. This was complicated by osteitis and a below-knee amputation was therefore performed.

Fig. 22. The same patient as in Fig. 21 four months after the amputation. The arteries between tibia and fibula are now dilated.

filled earlier than other branches of a similar or somewhat larger calibre proceeded towards this zone. One year later a spur had developed, towards which the same artery proceeded, but now less tortuously. Atrophy of the muscle had occurred and in its medial area the branches of the distal superficial femoral artery were wider.

The arteries which extended towards the distal femoral region in these patients filled with contrast earlier than other arteries of similar dimensions. In the youngest of these patients this finding was unchanged one year later.

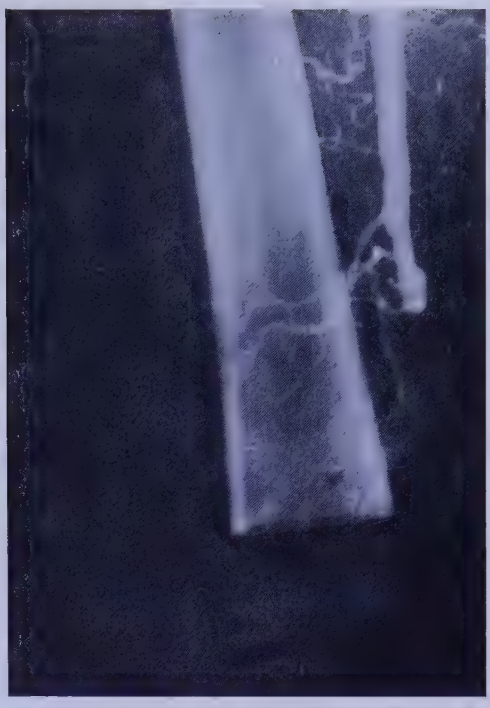

Fig. 23. (3961/61) 65 year old man. The arteriography was performed two weeks after the amputation which was caused by an accident. The surrounding areas of the distal femur are mainly supplied from the superficial femoral artery. Only a few arteries appear to arise from the deep femoral artery.

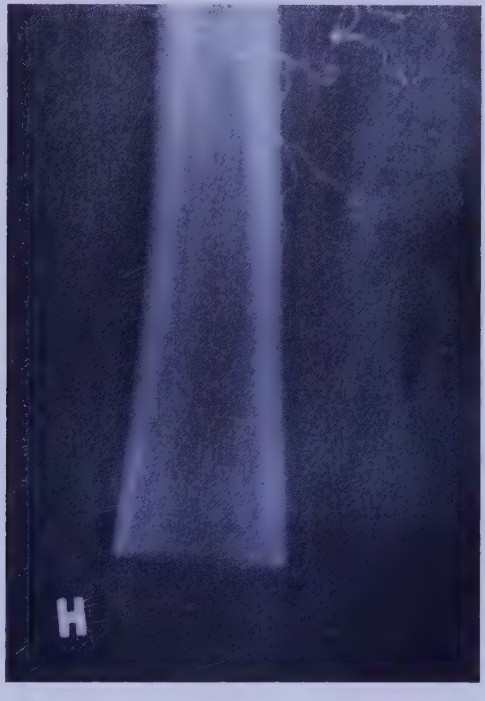

Fig. 24. The same patient as in Fig. 23. The contrast medium has been injected selectively into the deep femoral artery. Only a few arteries pass to the distal part of the stump.

Fig. 25. The same patient as in Fig. 23. The venous phase is shown. There is an increased number of rather dilated veins resembling the arteries.

Fig. 26. The same patient as in Fig. 23. Arteriography repeated after 9 months. In the distal part of the superficial femoral artery the lumen is now narrowed. The arteries are more tortuous around the distal end of the femur where there is some decalcification with an incipient exostosis. The muscles appear atrophied.

Fig. 27. The same patient as in Fig. 23. The venous phase of the arteriography is shown. The distal veins are distinct and tortuous around the distal femur. No findings like these in any other part of the stump.

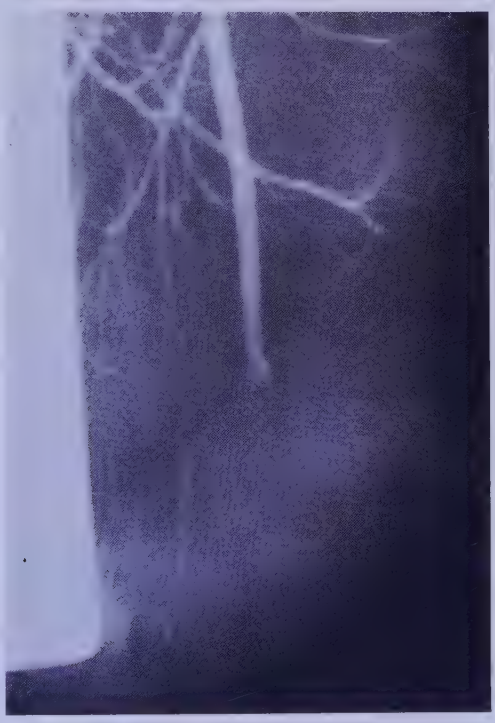

Fig. 28. (40306/62) Male above-knee amputee, 22 years old. Amputated 23 days ago because of trauma. Note the spiralled artery at the medial part of the femur, ending at the distal femur.

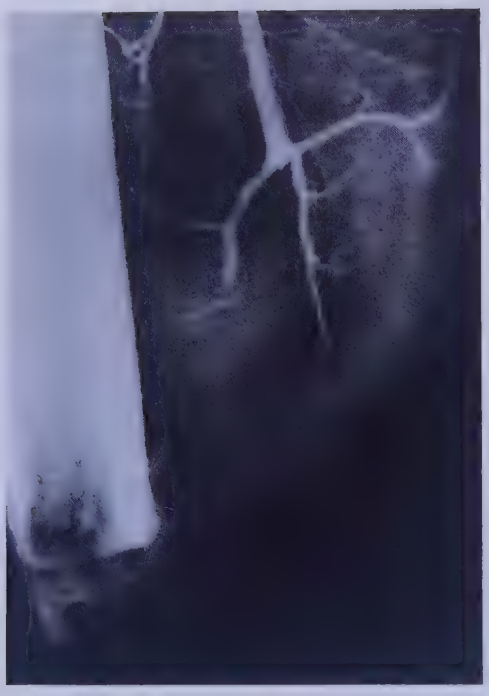

Fig. 29. The same patient as in Fig. 28, one year later. The small artery is still visible and connected with the spur. The muscles are atrophied and in the medial part of the stump distal, dilated branches from the superficial femoral artery are seen.

Discussion

Spiralled arteries and arterial richness

The results show that in 1/3 of the patients the arterial system in the amputation stump differs from that of the intact leg by the fact that a number of the arteries are distinctly tortuous. In such cases the stump is also relatively rich in vessels. Spiralled arteries are not observed in the corresponding region of the intact leg. In other clinical series, on the other hand, spiralled arteries have been found, for example, in collateral circulations beyond occluded main arteries. The reason for the spiral formation is not clear but it may be connected with "new formation" of the arterial system, either by the widening of already existing small vessels or by the actual formation of new vessels. When the large arteries are closed off during the amputation the pressure in them may be expected to rise about 10 mm Hg (demonstrated for example by Hasse et coll., 1959). The tissue trauma which occurs at the amputation is probably followed both by prolonged arterial

dilatation and by partial occlusion due to red-cell aggregation and stagnation (Gelin, 1964). This may result in increased pressure in some of the small arteries and thereby produce new circulatory paths. It is then conceivable that the spiral shape could be due to the fact that the new circulatory paths in the stump follow variable directions.

Such hypotheses do not explain why the spiral shape is sometimes absent. Other factors may possibly be involved, e. g. the metabolism of the local tissue and its consequent need of circulation, or the degree of retained nervous control over the smooth musculature of the arteries. The increased degree of richness of both arteries and veins may constitute the structural counterpart to a "shunting" of the blood. Hulth & Högström (1961) found a higher pO_2 in the femoral venous blood in an amputated leg compared with that of the intact leg, which supported the occurrence of "shunting".

Spur formation

An exostosis is often seen in the vicinity of the distal end of a femoral or tibio-fibular stump. In many cases vessels, both arteries and veins, are directed towards the spur. As a rule an artery is directed to the tip of this spur. This finding is in agreement with a report made by Dederich (1956), who on reamputation constantly found a vascular bundle, an artery and one or two veins, dorsal to the tip of the spur. He claimed that the spur occurred through traction (traction exostosis) associated with pulsations in the large ligated arteries, which are sutured to the periosteum of the stump. Another possible explanation is the occurrence of tissue change around the stump end, favouring new bone formation and at the same time causing local arterial dilatation and certain regional direction. A haematoma (Loon, 1959) may possibly be a provoking factor; this may give rise to a callus-like formation. In the present investigation it was not possible to demonstrate any systematic difference between cases with an exostosis with regard to operative technical procedure or such factors. It is probable, however, that a haematoma always occurs around the bone end, and this may be the site of calcium deposition as indicated in Fig. 28. Animal experiments of Erikson & Olerud (1965) also support the view that a haematoma may give rise to exostosis.

Arterial wall changes

In some patients arterial wall changes with marked protrusions into the lumen were seen, suggestive of arteriosclerosis. The vascular wall was studied

histologically in a few cases. In one above-knee and one below-knee amputee tissue samples were taken from the femoral and popliteal arteries, respectively, at reamputation. These arteries exhibited wall thickening and arteriosclerosis-like changes. Veins which similarly had remarkably thick walls were also found in these preparations. In 2 above-knee amputees where arteriography had shown the superficial femoral artery to be absent it was confirmed at operation that this artery was occluded, which may have been due to wall changes of a similar type.

The increased incidence of these arterial changes in the amputated legs is worthy of note. This may be compared with an observation of Nylander (1962), who found very pronounced arteriosclerosis in the leg arteries of a young poliomyelitis patient. He considered this change to be connected with reduction in blood flow. This may possibly hold also for the main arteries of amputation stumps, as their walls are probably subject to alterations in pressure and flow conditions.

Standing waves (Arterial waves)

The arterial wave phenomenon described by Wickbom & Bartley (1957), Theander (1960), and Mayall (1964), among others, was found to be relatively common in this amputation series. These so-called standing waves were interpreted by Theander as a physical phenomen with no direct relationship to wall changes, and in the great majority of his cases was associated with peripheral arterial block. Mayall made in vitro experiments in which a non-turbulent stream of water flowed through a transparent horizontal tube. Urografin 60 % was injected into the stream of water and formed a separate lower layer. According to Mayall waves occurred at the interface between these fluid layers, and he regarded this as support for his view that the standing wave phenomenon did not exist. It may thus possibly be interpreted as a sign that the contrast medium sedimented in the arteries where the phenomenon occurred. Its physiological significance in man is, however, not yet clear.

Venous system

Inman, Barnes, Levy, Loon & Ralston (1961) and Gillis (1964) consider that the venous pattern is altered after an amputation. Impairment of the venous return occurs with resulting stasis. This is believed to cause dilatation of the medullary canal, and according to Gillis the delayed venous return is possibly especially common in painful amputation stumps.

In the present investigation the venous system was found to be distinctly

filled with contrast in the majority of those patients with a high degree of vascular richness and tortuous arteries. The veins were wide and had the same tortuous course as the arteries; in some cases there were local dilatations and a plexiform arrangement in the stump. It was not possible, however, to study the deep veins in detail and thus to corroborate Loon's observation (1959) that in intraosseous phlebography the deep veins did not fill. Phlebography was only performed by the present author on 2 below-knee amputees, and its chief purpose was a method study in connection with plethysmography (see chapter 4). It was considered that the results of this investigation, which is often painful, are much too difficult to reproduce for it to come into general use in this connection. Animal experiments with Thorotrast have shown that the venous system fills only incompletely in both intraosseous and intravenous phlebography (Ekholm, Erikson & Skoglund, 1964).

Repeated investigations on the same amputation stump on different occasions from the immediate post-operative period onwards were possible in a few cases. The results from these cases did not differ from those from the rest of the material. Dilatation of the distal arteries and their orientation towards the bone stump appear to occur at a relatively early stage post-operatively. The arteries which travelled towards the distal region in the stumps in the two newly amputated patients, described in section III of this chapter, became filled earlier than the other similar-sized branches in the stump, and in one of them this condition remained unchanged on examination one year later. This may indicate a decrease in the peripheral blood flow resistance in this region of the stump during healing after the operation. Later in the post-operative course a change of the arteriosclerotic type may occur in the arterial walls.

Summary

1. Different types of arterial patterns were found in the amputation stumps studied. One group of patients exhibited an ordinary arterial network, a second group an increased and a third group a pronounced arterial network, rich in arteries, a large number of which were spiralled. The venous system was in many cases markedly developed when the arterial richness was increased.

2. At the end of the amputation stump arteries and veins in many cases showed relationship with an exostosis, which was of very frequent occurrence.

3. Arteriovenous anastomoses were frequent, especially in below-knee stumps.

4. Wall changes reminiscent of arteriosclerosis were more frequent in the main artery of the amputation stump than in the intact leg.

5. The standing wave (arterial wave) phenomenon was observed in some cases.

6. The results in amputees investigated on repeated occasions after the amputation indicated that the principal arrangement of the arterial system, and probably also of the venous system, was at a relatively early post-operative stage; these results also indicated that there may have been some local decrease in peripheral resistance in the region around the distal bone end of the stump.

CHAPTER III

Diameters and rate of contrast passage in the main arteries of amputated and intact legs

Arteriographies on intact and amputated legs have been studied with reference to the inner arterial diameters (defined as the diameter of the contrast filled lumen of the artery) and the rate of contrast passage with a view to determining differences in this respect between amputated and intact legs.

Review of the literature

No systematic study of the inner arterial diameters in amputees appears to have been made. Hasse et al. (1959), on the basis of an arteriography in a below-knee amputee, discussed the cause of the decreased arterial diameters in the amputated leg compared with the intact leg. They considered that reduction in flow was the most probable cause of the decrease in the lumina of the arteries.

The information extractable regarding the blood flow from the contrast filling and contrast passage on arteriography has long been discussed in the literature. A comprehensive review of this literature was published by Güntert and Zimmer (1957), who made kymographic studies of the movement of contrast in vessels. They pointed out that a roentgenological method which is based on the movement of the contrast medium does not provide any direct information of the mean blood flow but only on the momentary movement of the contrast medium in the blood vessels. Erroneous results may be obtained because the contrast media hitherto used differ from the blood with respect to density and viscosity. Apart from the fact that the contrast media thus probably move more slowly, they may also sediment to the declivitous parts of the vessels under certain conditions. Kjellberg (1943) showed this in model experiments with thorotrast as the contrast medium.

Anschütz & Heuck (1959) reported arterial flow measurements with roentgenological methods whereby the velocity of a small quantity of contrast medium was used as a measure of the flow, and serial exposures and a film changer were used.

Heuck (1962) described studies on patients with diagnosed aortosclerosis

or peripheral arterial blood flow disturbance, and also a group of healthy subjects. The picture frequency in these investigation was 6/sec when an Odelca Rapidix cassette was used, and 40/sec using a Cinelix image intensifier. A study of the correlation between the true and the calculated flows in model experiments indicated an error of the method of about 5 % (Anschütz & Heuck, 1959, Heuck, Anschütz & Schwarzkopf, 1963). These authors gave very little information, however, on the procedure of the control experiments.

Though the systematic error of the method has as yet not been satisfactorily determined, it probably gives some information on the blood flow, however, and permits some comparisons between different patients. Though the values of the flows are calculated as ml/min this must be regarded as a purely empirical estimate for comparative purposes only. The blood flows obtained are minimal values since only the contrast medium passing through large arterial trunks is recorded, and it is not known how much passes through the small branches. Similarly, owing to the higher specific weight of the contrast medium, the velocity of the contrast column is slower than that of the blood.

Methods

The diameter and linear velocity in the contrast column were measured on films obtained at the arteriographies, which have been described in chapter 2.

The diameters were measured in the superficial and deep femoral arteries 8 cm below the lesser trochanter on both the intact and amputated leg of above-knee amputees. This level was chosen because it fitted within the picture field even in long thigh stumps. In below-knee amputees the diameters were measured in the popliteal and superficial femoral arteries at a level with and 10 cm and 20 cm above the knee joint.

For the measurements a magnifying glass with a built-in scale was used, which permitted readings within 0.1 mm. Independent duplicate measurements were made of arterial diameters on 30 extremities, the mean value being 4.61 mm and the error of mean of measurement 0.10 mm.

The linear velocity of the contrast column in the superficial femoral and popliteal arteries was measured in above-knee amputees in the region distal to the level at which the diameters were measured, and in below-knee amputees in the distal superficial femoral artery and popliteal artery cranial to the knee joint. The same vascular regions were used bilaterally in the respective groups of amputees.

The picture frequency was 1 frame per second, and the distance which the vertex of the parabolic front of the contrast column moved between two consecutive exposures gave the velocity in cm/sec. In a small number of arteriographies the contrast medium had reached so far distally in the arteries that the velocity could not be calculated in the desired regions. This was due as a rule to the fact that photographing was started too late after the contrast injection, and occurred especially when the contrast medium was injected by hand. These investigations have been excluded from the velocity measurements.

The picture frequency was adjusted with a programme selector of standard construction (Elema-Schönander AB, Solna, Sweden). In 30 measurements the time never deviated more than 0.1 sec from the mean value. The exposure time was < 0.023 sec.

The movement of the contrast medium was measured in units of 1 mm, and independent duplicate measurements in 30 patients showed a mean figure of 12.0 cm/sec and an error of the mean of 0.42 cm/sec. The apparatus and focus-film distance were identical in all arteriographies. The patients lay on the same examination table, which was movable and was placed in between the tube and the film changer. The distance between the object, i.e. the femoral artery, and the film was thus only varied here by the volume of soft tissues on the dorsal side of the thigh. The enlargement of the vessels and the distance travelled by the contrast medium could therefore vary somewhat. None of the patients were adipose, all being of normal body weight. Since the mean distance between the object and the film varied between 17 and 23 cm the enlargement factor could change from 0.80 to 0.84 when the film-focus distance was 125 cm.

The velocity measured on the arteriograms in the centre of the vessel is in the following text called v_{max}. If the flow is F and the cross-section A the linear mean velocity $\bar{v}$ is F/A.

Poiseuille's law gives

$F = \Delta P \cdot \pi/8 \cdot 1/\eta \cdot R^4/l$, where ΔP is the pressure difference along the length l and η is the coefficient of internal friction (Ruch & Fulton, 1960).

Thus $\bar{v} = \Delta P \cdot 1/8\ \eta \cdot R^2/l$.

$v_{max} = \Delta P/l \cdot R^2/4\eta$

Thus $\bar{v} = v_{max}/2$

To determine the effect of the contrast medium on the blood flow, the flow was measured by venous occlusion plethysmography during the arteriographies in 5 patients. The methods are described in Chapter IV.

In 4 patients the flow was measured in the stump, and in 1 patient in the intact calf.

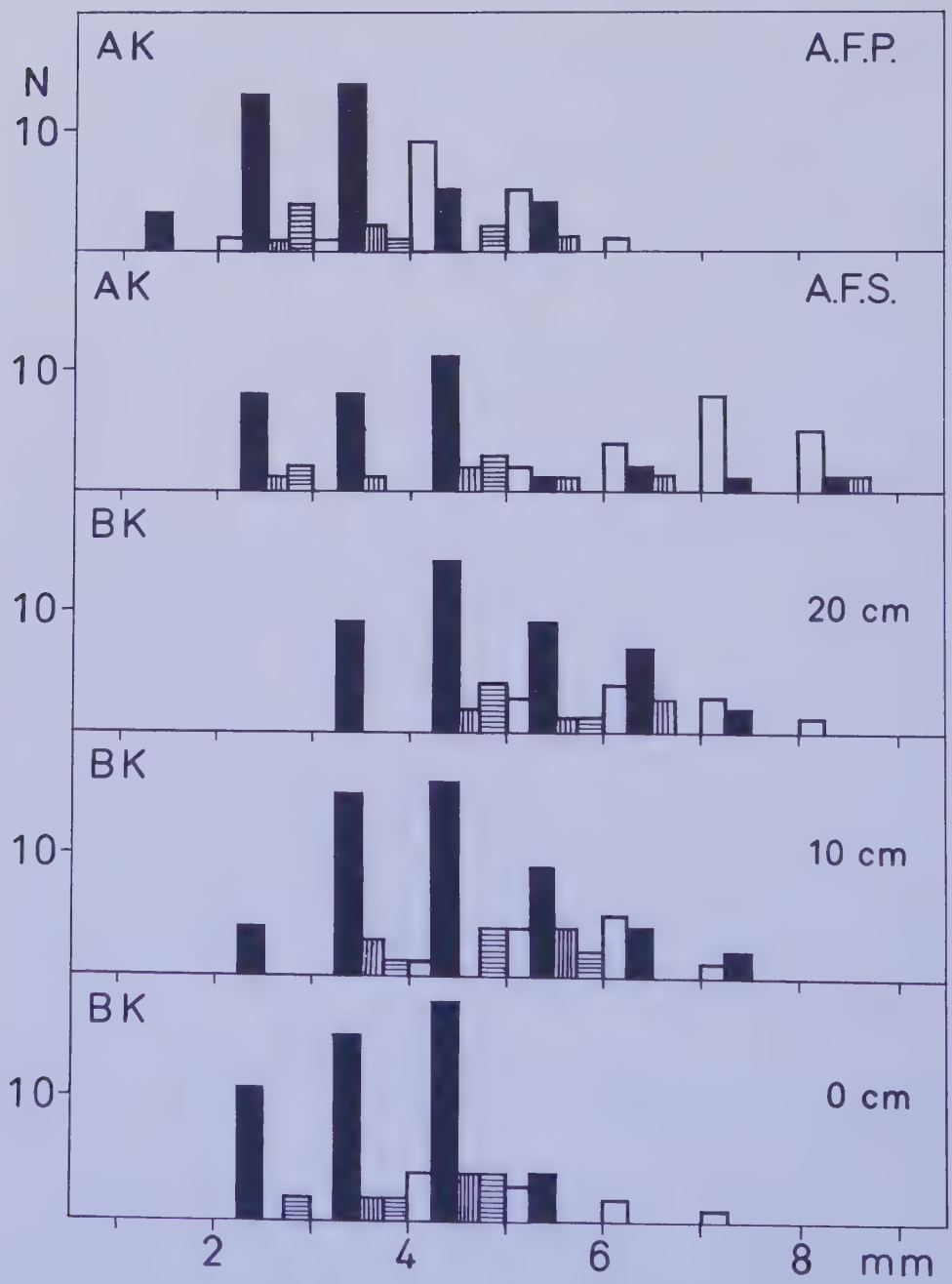

Fig. 30. The frequency distributions of arterial diameters at different levels.

A. In above-knee amputees (AK) the superficial (AFS) and deep (AFP) femoral arteries were measured at a level 8 cm below the minor trochanter of the femur (TMF). In below-

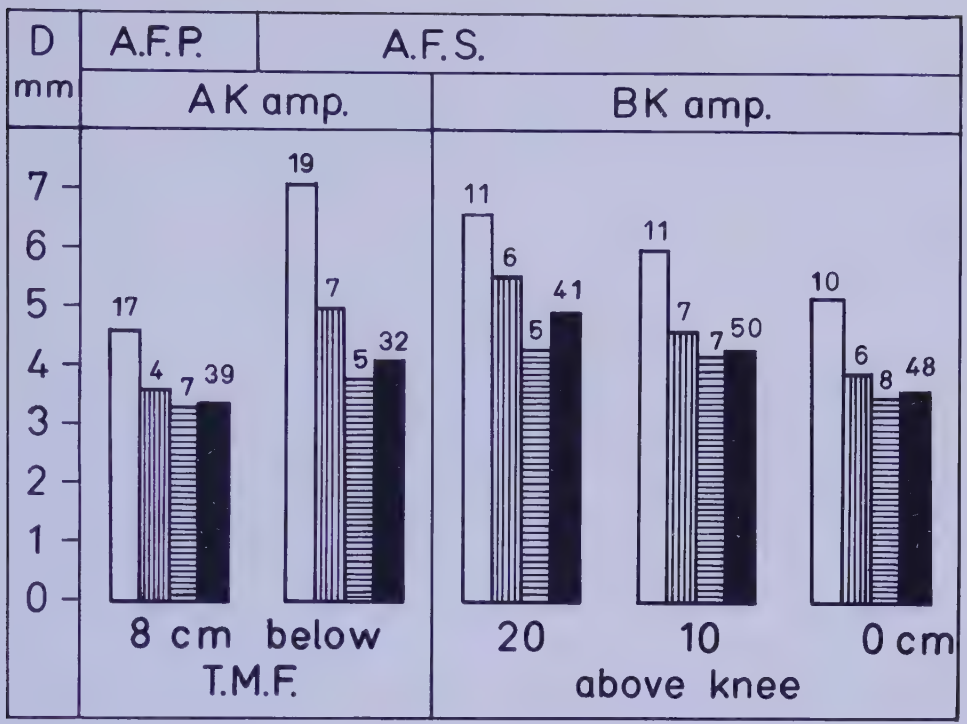

Fig. 31. The average arterial diameters at different levels. The figures above the bars give the number of observations. For notations see Fig. 30.

Results

A. The results of the diameter measurements are given in Figs. 30 and 31. (The values are not corrected with regard to magnification.) The following observations were made:

When bilateral measurements were made, the diameters were found to be reduced in all stumps compared with the intact legs.

In 19 intact legs of 32 above-knee amputees the mean diameters in the superficial femoral artery 8 cms distal to the lesser trochanter was 7.1 mm, and the mean diameter in all 32 stumps measured at the same level was 4.1 mm. In the group investigated within a year after the amputation, it had

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knee amputees (BK) the superficial femoral and popliteal arteries were measured at the knee joint and 10 and 20 cm above it.

The markings of the bars are as follows: unfilled = intact legs, vertical hatching = stumps up to one year after amputation, horizontal hatching = stumps 4–6 years after amputation and solid = all stumps irrespective of time after amputation.

decreased to 5.0 mm (7 patients) and in the 5 patients with an observation period of 4–6 years it had decreased to 3.8 mm. The reduction in the diameters was less pronounced in the deep femoral artery. In 17 intact legs the mean diameter was 4.6 mm, and in the 39 above-knee amputees, where this was measured, the mean value was 3.3 mm. Within a year after the amputation it had decreased to 3.6 mm in 4 patients, and 4–6 years after the amputation it was 3.3 mm in 7 patients.

In below-knee amputees there was a similar reduction in the arterial diameters in the amputated leg. In 11 patients the mean diameter in the intact leg, 20 cm above the knee joint, was 6.6 mm. In 41 lower leg stumps the diameter of the superficial femoral artery at the same level was 4.9 mm. Of these, 6 patients who were examined within a year after the amputation had a diameter of 5.6 mm, and 5 who were examined 4–6 years after the amputation 4.3 mm. At the 10 cm level above the knee joint, the mean diameter in the superficial femoral artery in 11 intact legs was 6.0 mm, and in 50 lower leg stumps 4.3 mm. In 7 patients after 1 year and in 7 patients after 4–6 years the mean diameter was 4.6 and 4.2 mm, respectively. At the level of the knee joint the mean diameters in 10 intact and 48 amputated legs were 5.2 and 3.6 mm, respectively. Of these latter, 6 stumps were examined within 1 year and 8 within 4–6 years, and their mean diameters were 3.9 and 3.5 mm, respectively.

There thus appears to be a progressive reduction of the arterial diameters, which is most pronounced in above-knee amputees in the superficial femoral artery, where the mean diameter in the 32 thigh stumps was 58 % of the mean diameter in 19 intact legs. In the deep femoral artery there was a corresponding reduction to 72 % of the intact leg's artery. In all below-knee amputees the diameter for 20 cm and 10 cm above the knee joint and that at the knee joint was reduced to 73 %, 72 % and 69 % of that of the intact leg, respectively.

B. The results from the measurements of the movement of the contrast in the arteries are shown in Tables 9 and 10 (the values are not corrected with regard to magnification). In estimating the velocity any deviation from the horizontal plane was neglected. The flow was obtained from the formula $v_{max}/2 \cdot \pi \cdot d^2/4 \cdot 60/100$ ml/min, where $v_{max}/2$ was the mean linear velocity of the contrast in cm/sec and d the diameter of the artery in mm, measured at the levels mentioned previously. In above-knee amputees these flows varied in 20 amputation stumps between 14.3 and 37.8 ml/min and in 12 intact legs between 113 and 334 ml/min. In below-knee amputees the flow to 39 stumps at knee level varied between 12.9 and 42.3 ml/min, and in 9 intact legs between 36.9 and 163 ml/min.

Above knee amputees grouped according to the linear velocity of the contrast column in cm/sec									
	Amputated legs				Intact legs				
	0 - 5	6-10	11-15	16-20	6-10	11-15	16-20	21-25	26-30
No.	6	7	6	1	2	3	2	2	3
Velocity ($v/_{max}$) mean value cm/sec.	4.2	7.8	12.4	19.0	9	13	18.5	21	28
Diameter mean value mm	3.8	4.1	3.6	2.9	7.3	6.6	7.7	6.9	7.1
Flow mean value ml/min	14	29	38	38	113	134	258	236	334

Table 9. The diameters and flows in above knee amputees.

Blood flow = $v_{max}/2 \cdot d^2/4 \cdot \pi \cdot 60/100$ ml/min.

Diameter = d in mm: diameter of the contrast-filled lumen of the artery.

Velocity = v_{max} in cm/sec: the velocity of the vertex of the front of the contrast medium.

Below knee amputees grouped according to the linear velocity of the contrast column in cm/sec								
	Amputated legs				Intact legs			
	0 - 5	6-10	11-15	16-20	0 - 5	6 -10	11-15	16-20
No.	16	13	7	3	2	3	3	1
Velocity ($v/_{max}$) mean value cm/sec.	3.8	7.5	12.4	19	4.5	6	12	18
Diameter mean value mm	3.8	3.9	3.8	2.7	5.9	6.0	5.3	6.2
Flow mean value ml/min	13	27	42	33	37	50	80	163

Table 10. The diameters and flows in a number of below-knee amputees.

Blood flow = $v_{max}/2 \cdot d^2/4 \cdot \pi \cdot 60/100$ ml/min.

Diameter = d in mm, diameter of the contrast filled lumen of the artery.

Velocity = v_{max} in cm/sec, the velocity of the vertex of the front of the contrast medium.

Type of amputation	Patient No.	Arterial blood flow ml/min		Volume in measuring segment at plethysmography ml		Stump length cm	Quotient between flow in amputated and intact leg
		Amputated legs	Intact legs	Amputated legs	Intact legs		
Above knee	1	11	358	460	380	25	0.03
	2	11	255	755	880	26	0.04
	3	16	255	470	695	21	0.06
	4	17	200	530	788	25	0.09
	5	24	258	420	600	28	0.09
	6	28	129	550	730	20	0.21
	7	32	315	604	702	27	0.10
	8	38	90	550	790	32	0.41
	9	38	114	515	975	30	0.32
	10	46	330	540	600	21	0.14
	11	69	130	450	1000	32	0.53
Below knee	1	3	10	220	545	17	0.30
	2	10	54	283	460	12	0.17
	3	15	60	230	300	26	0.24
	4	15	100	-	-	14	0.15
	5	15	64	295	420	19	0.25
	6	24	77	345	480	16	0.31
	7	27	52	420	515	15	0.50
	8	60	163	300	637	12	0.37

Table 11. The table shows the roentgenologically measured flows (arterial blood flow) in the 11 above-knee and 8 below-knee amputees. To give an idea of the volume proportions at comparable levels between amputated and intact legs, the volume covered by the measuring cuff for plethysmography is given (see further chapter IV). In the above knee amputees the distance between the lesser trochanter and the end of the stump has been given as the stump length, and in the below-knee amputees the distance between the knee joint and the stump end.

These results also show that a small diameter does not necessarily mean a low flow in the main arteries of the amputation stump.

In 11 above-knee and 8 below-knee amputees the diameter and contrast passage velocity were measured bilaterally at the same levels, and a comparison was possible between the flows in the arteries at the same level (see Table 11 and also the discussion in this chapter).

C. As may be seen in Fig. 32 the results from the blood flow measurements show a relatively rapid flow increase which occurred after 20 ml 60 % Urografin had been injected into the superficial femoral artery. For the amputees the measuring sites were the amputation stump in 4 patients and the intact calf in 1 patient. In 1 patient the blood flow increased tenfold, and in the other patients the increase was smaller, the smallest increase being four-fold. In the 5 patients the flow returned to the original value within 60–120 sec.

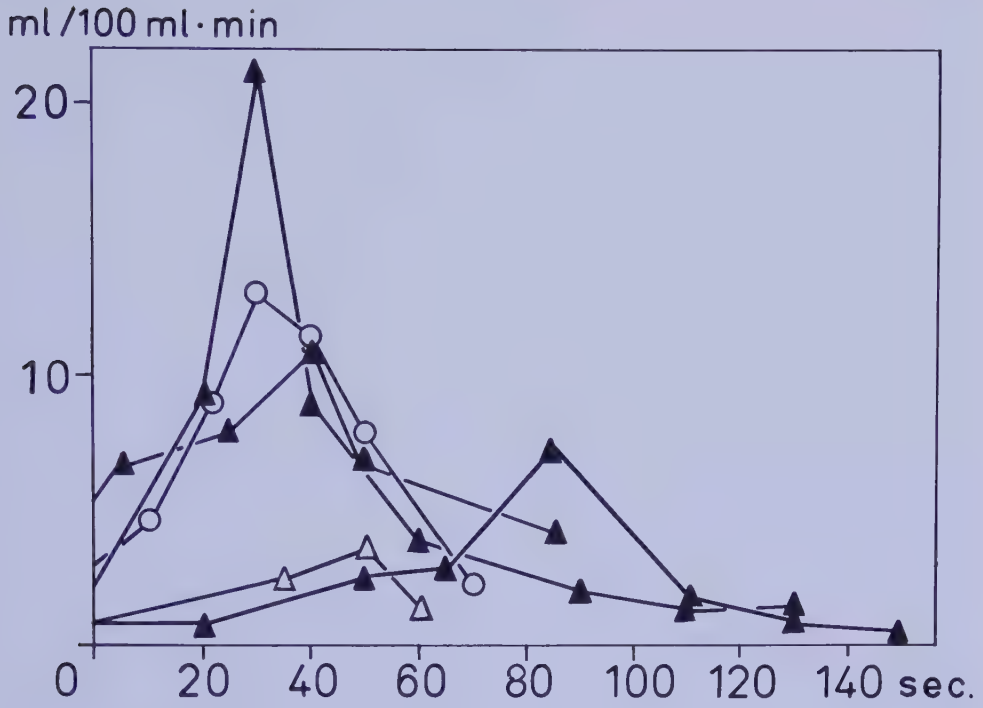


Fig. 32. The effect of the contrast medium, Urografin 60 %, on the blood flow in 4 below-knee stumps (▲) and in the intact leg of an above-knee amputee (○). The injections were made at time 0 sec.

Discussion

The diameters in the superficial and deep femoral arteries are reduced in an amputation stump. In their discussion on the reason for this, Hasse et al. (1959) concluded that it was caused by the decrease in flow in the amputation stump.

If the linear velocity of the contrast column is assumed to be proportional to the blood flow, it is evident from Tables 9 and 10 that a small diameter need not mean a reduced blood flow.

The resting flow in these patients with healthy vessels is not determined by the anatomical dimensions of the large arteries but probably by the physiological status of the smallest arteries, arterioles, capillaries and venules. This would seem to explain the fact that in some isolated cases flow through a narrow superficial femoral artery may be more rapid than in a wide artery.

It has been considered that roentgen contrast media containing com-

pounds of iodine may have some effect on the arterial diameters. Sgalitzer (1937) claimed that the arteries were dilated, with a resulting increase of blood flow. Thus if one leg is investigated 10–20 min before the other an excessive diameter could be obtained at the second arteriography if the excretion of the contrast medium is delayed. Lindgren & Törnell (1958), in cat experiments, found an increased arterial blood flow with contrast media containing iodine.

In order to determine the effect on the blood flow, the author studied the flow in amputated and intact legs in 5 patients, by means of venous occlusion plethysmography. The method is described in chapter IV.

In these patients after intraarterial injection of 20 ml 60 % Urografin, the blood flow increased, and within 60–120 secs it had returned to the original resting value (Fig. 33). The contrast medium, Urografin, is rapidly excreted so that the blood concentration becomes low. The type of contrast medium used by Sgalitzer is not used nowadays.

The contrast medium is visible in the arteries for about not more than 10–15 secs. The measurements of diameters and velocities in the contrast columns in the large arteries were performed during the first 3–4 seconds, and it was assumed that the contrast medium would not yet have had any effect on the arterial walls and that the values obtained would thus reflect the resting blood flow conditions.

It has not been possible in these investigations to synchronize the exposures with the ECG cycle. Thus variations in the velocity during the pulse cycle introduce some uncertainty.

Because of the length of time between exposures (1 second) the relative lengths of time of the slow and fast phases of the pulse cycle can vary within this period.

Assume that the time for one pulse cycle $= t_p$ and the time between two consecutive exposures t_f. Further, $t_f - t_p = k$. Period t_p consists of a rapid phase of 'a' sec and a slow phase of 'b' sec, thus $a + b = t_p$.

For t_f sec the contrast medium moves s cm
„ t_p „ „ „ „ „ s_p cm
„ a „ „ „ „ „ s_a cm
„ b „ „ „ „ „ s_b cm

Let us discuss the following a) $o < k < a$ and b) $k \geq a$

a) the maximal distance which the contrast medium moves during t_p (1 sec)

$$s_{max} = s_a + s_b + s_a \cdot \frac{k}{a}$$

the smallest movement which the contrast medium makes during t_p (1 sec)

$$s_{min} = s_a + s_b + s_b \cdot \frac{k}{b}$$

$$s_{max} - s_{min} = \Delta s = k\left(\frac{s_a}{a} - \frac{s_b}{b}\right)$$

b) $$s_{max} = s_a + s_b + s_a + s_b \frac{(k-a)}{b}$$

$$s_{min} = s_a + s_b + s_b + s_a \frac{(k-b)}{a}$$

$$\Delta s = s_a - s_b + s_b \frac{(k-a)}{b} - s_a \frac{(k-b)}{a}$$

$\Delta s = 0$ when the velocity does not vary during the pulse cycle, i. e.

$$\frac{s_a}{a} = \frac{s_b}{b}$$

similarly

$k = O$ when the exposure frequency and pulse frequency are the same.

In the present material the pulse varied between 60 and 85 beats/min. In the study of Anschütz & Herberger (1962) movement in the intact leg of the contrast medium in the pulse cycle is shown in a figure. In this study $k = 0.2$ sec, $a = 0.3$ sec, $b = 0.5$ sec, $s_a = 7$ cm and $s_b = 11$ cm, $v_{max} = 22.7$ cm and v_{min} 22.4 cm, i.e. $\Delta s = 0.2$ cm.

I have assumed that the velocity variations in the healthy leg of an amputee are similar to those in the healthy subjects studied by Anschütz et al. No investigation appears to have been made on the velocity variations during the pulse cycle in amputated legs. They may thus be proportional to those in the intact leg or less pronounced as is the case with luminal reduction in arteriosclerosis.

The exposure time was < 0.023 sec and the movement of the contrast medium during the exposure thus gave blurrings and uncertainty. This was $< v_{max}$. 0.023 mm. The systematic errors decrease in importance in comparisons between amputated and intact legs investigated with the same technique. There remain, however, errors of measurement, variations in the exposure frequency and the error which occurs when the velocity cannot be measured between identical points on the pulse cycle. These errors are not so large, however, as to notably affect the order of size of the quotients given in Table 11.

The formulae used for determination of the blood flow are based on the assumption that the advancing front of the contrast column has a parabolic shape. This can be seen in the arteriograms.

The linear velocity of the contrast calculated from the rate of progress of the contrast front in the arteriograms is the maximum linear velocity along the axis of the vessel. For calculation of the true rate of flow, however, the mean linear velocity must be used. It is not clear in the papers of Heuck & Anschütz (1959) which velocity they have used. The use of a high speed camera ought to make the method for roentgenological determination of flow more useful.

In below-knee amputees a comparison can be made, with some approximation, between the blood flow at rest in the amputation stump and the intact leg. Let the volume of the intact leg distal to the knee joint be V ml, the volume of the amputation stump distal to the knee joint X ml, and the roentgenologically measured flow in these legs F_V and F_X ml/min, respectively, at the joint level. A comparison between intact and amputated legs was made in eight below-knee amputees (see Table 11). In this table the eight patients have been grouped according to increasing flows in the amputated leg. The quotient F_X/F_V is given on the right hand side of the table and varies between 0.15 and 0.50 for below-knee amputees. The ratio X/V cannot be given exactly for the eight patients. However, the volume of the amputated leg from the measurements of tissue volume can be estimated at plethysmography (Table 11) as approximately 2/3 of the intact leg at the same level. The amputation stumps extend to about 16 cm below the knee joint. On the basis of these data the quotient X/V can be assessed as between 0.20 and 0.13 in the patients investigated, i. e. the volume of the intact leg distal to the knee joint is assumed to be 5–7 times greater than the amputation stump. From a comparison between X/V and F_X/F_V it is evident that in 4 patients F_X/F_V was between 0.30 and 0.50. It cannot be assumed that in these patients the ratios between the tissue volumes are the same as between the blood flows. It is probable that the resting blood flow in these amputations stump is relatively higher per tissue volume than in intact legs, on corresponding levels.

A similar comparison was made for above-knee amputees. In these patients the distal part of the amputation stump receives its blood supply via branches of both the superficial and the deep femoral arteries. Even if an approximate estimate of the flow in the superficial femoral artery can be made at the level of 8 cm below the lesser trochanter, it is not possible to determine with certainty the magnitude of the tissue volume through which this blood is distributed. It can, however, be regarded as small compared with the

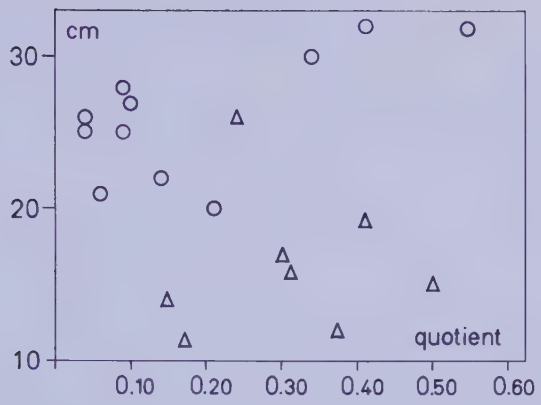


Fig. 33. The stump length is the ordinate. In above-knee amputees, 0, this is measured on the roentgen film and constitutes the distance from the lesser trochanter to the tip of the stump. In the below-knee amputees, △, the stump length is the distance from the knee joint to the end of the stump. Along the abscissa are given, for above-knee amputees, the ratio between the flow in the superficial femoral artery in the amputated and intact leg, and for below-knee amputees the corresponding ratio for the flow in the distal superficial femoral and popliteal arteries.

volume in an intact leg within which the blood in the superficial femoral artery at the same level will distribute. Table 11 shows that among the 11 above-knee amputees also the ratio between the flow in the stump and the intact leg may differ from that between the tissue volumes. In 7 of these patients the quotient was 0.14 or less. In 4 patients it varied between 0.20 and 0.53, and in these 4 patients the flow through the tissues of the amputation stump may thus be proportionally greater than in the intact leg.

Although the tissue volumes cannot be determined exactly in the above- and below-knee amputees, the results show a tendency in a number of amputation stumps towards a high blood flow compared with the intact legs. Because of the difficulties in determining the volume within which the contrast distributes when it has passed a given level, it was decided to use the length of the stump as a parameter indicating the volume. This is obviously an oversimplification; but as may be seen in Fig. 33 there is a tendency to wide scatter in the ratios between the flows in amputated and intact legs in patients with stumps of roughly equal length and hence of volumes which cannot differ so greatly from one another. This method does not at present allow accurate measurements, and the results should therefore be compared with and complemented by those obtained from plethysmography.

Summary

The diameters of the main arteries of the stumps were always smaller than those of the intact legs and there was a tendency to decreasing diameter with increasing observation time. As a rule the rate of movement of contrast medium was lower in stumps than in intact legs.

The measurements of the arterial diameter and movements of the intra-arterial contrast column in amputated and intact legs show that a change of the diameter does not necessarily reflect a corresponding change of the blood flow. This may be estimated, although somewhat approximately, from the movement of the contrast medium in the large arteries. It was also shown that on comparison between the blood flows measured in this way and the approximate tissue volumes, some support is obtained for the view that there is an increased blood flow per tissue volume in certain amputation stumps. An extended study of problems connected with the observation of varying flows, with a proven method whose uncertainties are better known, i.e. venous occlusion plethysmography, is described in chapter IV.

CHAPTER IV

Blood flow at rest and during reactive hyperemia

Amputation stumps are considered to have a lower skin temperature than intact legs (Loon, 1959). Loon investigated 31 patients who were amputated without any known vascular disease, and 12 who were amputated for reasons of such disease. He found no correlation between the degree of phantom or stump pain and the extent to which the stump temperature fell during the initial period of exposure to cold or the extent of stump warming during generalized vasodilatation. Erikson & Hulth (1962) found, however, that warming of the body gave rise to an increase in the temperature of the skin of the stump to a level higher than that of the intact leg in patients with phantom pains.

In oscillometric tests the arterial pulse in the stump was found by Loon (1959) to be significantly smaller than in the normal limb. He also stated, however, that both the local sensory innervation and the local cutaneous blood supply were normal in his cases.

From his findings Loon concluded that there must be a reduction of total circulation in the amputation stump. Leriche (1949) considered, on the other hand, that in a number of stumps there was probably hypercirculation, i. e. excessive blood flow. The methods used for estimating the blood flow have been relatively unreliable, however. Loon, for example, used the methods of temperature measurement and oscillometry, while Leriche drew his conclusions on the blood flow from arteriographies.

The investigations described in the chapter and in chapter VI were made in an attempt to establish:

1. The resting blood flow in the stump and intact leg.
2. The maximum blood flow during reactive hyperemia in the stump and intact leg.
3. The proportions of the different tissues in the extremities and their relation to the blood flow.
4. The relationship of the resting flow to the skin temperature in the stump and intact leg.
5. Possible relationships between arteriographic findings and different blood flows.

6. Possible relationships between different degrees of symptoms, especially pain, in the amputated leg, and different blood flows.

The results from questions 5 and 6 are presented in chapter VI.

Material of patients

A total of 47 patients, i. e. 7 women and 40 men were investigated. Three patients had bilateral amputations, all of them below the knee. The age distribution may be seen in the diagram showing the variation of the blood flow with increasing age (Fig. 34).

None of the patients had arterial hypertension or symptoms of vascular disease.

Methods

Blood flow measurements. The method used is a modification, introduced by Graf & Westersten (1959), of the flexible extremity plethysmography originally described by Dohn (1956). Graf & Westersten found excellent agreement between the measured and the true volume change in the measuring region used for the occlusion plethysmography. The apparatus and method were studied further by Graf (1964), who calculated the accuracy in all the regions he measured. The method may be therefore considered well tested and reliable.*

For amplification and recording of the volume changes a direct-writing apparatus was used (Mingograf 42, Elema-Schönander AB, Solna, Sweden).

The investigations were always begun in the morning, and the patients ate a light meal beforehand. They rested for at least 1/2 hour on the examination table with the measuring cuffs in situ, and they were asked to relax and keep as still as possible. The room temperature was about 23° C and the patients felt comfortably warm. They were covered by blankets except on the areas where the cuffs were placed.

For the investigation of the intact leg an arterial occlusion cuff 6 cm wide was placed distally to the 5 cm wide measuring cuff. Owing to lack of space on the stump this was not possible on amputated legs. The width of the venous occlusion cuff was 6 cm.

In the investigation of below-knee amputees segmental cuffs were as a rule placed on both the thigh and the calf. The measuring cuffs were placed

* The auther wishes to thank Dr. Klaus Graf for his assistance in starting this investigation.

bilaterally at similar levels on the calf with their proximal edges 9–11 cm distal to the knee joint, and also lay at about 15 cm proximal to the knee joint of the intact leg. In some above-knee amputees bag cuffs were used (Fig. 40). In this investigation the methods of Landowne & Katz (1942 and Graf 1964) were used. The pressure in the venous occlusion cuff was 50 mm Hg and in the arterial 250 mm Hg. Reactive hyperemia was produced by arterial occlusion, with use of an inflated cuff for 8 min.

Skin temperature measurements. In 33 patients, 2 of whom had bilateral amputations, the skin temperature was measured at corresponding points on the stump and intact leg on the ventral, medial, dorsal and lateral sides of the extremities. An electric thermometer was used, with an accuracy of 1/10° C (TE-3, Ellab, Copenhagen, Denmark).

Roentgenological measurement of the tissue proportion. In order to determine the proportions of the different tissues enclosed by the measuring cuffs the soft tissue roentgen technique (Frantzell, 1951) was used. As a rule the extremities were photographed with the cuff in place (Fig. 40). In the other patients, who were investigated without the cuff in situ, the level of the cuff on the leg was noted at the plethysmographical investigation and the corresponding part of the leg was then examined roentgenologically. Care was taken to prevent compression or deformation of the tissues. The patients were examined in the recumbent position and always with the same distance between focus and film (125 cm) and with the film cassette immediately under the patient. A small number of patients were examined with both lateral and frontal projections, and the remainder with frontal only. It was assumed here that the $(\text{diameter})^2$ was proportional to the cross section surface area of the extremity and that the cross sections of the musculature, bone and whole leg had the same geometrical outline.

The approximation is obviously rough as regards the bones in the lower leg, since the cross section of both the fibula and the tibia must be taken into consideration; there is thus a systematic error in the calculations for these patients. The diameter of the fibula is about 1 cm and the ratio of its cross section surface area to the total surface area of the lower leg cross section is $1/D_t^2$ where D_t = the total diameter. In the great majority of cases this is larger than 10 cm. Thus the proportion of the lower leg bone is erroneously small if that of the fibula is neglected in the measurements, i.e., 1 per cent should be added to the proportion of the whole bone. Similarly the approximation of a constant ratio of the same geometrical outline between the cross section for the total leg and the muscular part contributes an error.

On calculating the tissue proportions enclosed in a bag-cuff the volumes have been approximated to half spheres. Thus the percentage of muscle is

$h_1/h_2 \cdot (D_m/D_t)^2$ where h_1 is the distance from a plane through the proximal borderline of the cuff to the most distal part of the muscle, h_2 the corresponding distance to the stump end and D_m the muscle diameter.

Independent double determinations of diameters were made on 30 extremities with a measuring unit of 1 mm. The total diameter, muscle diameter and bone diameter were measured, the mean figures obtained being 132,4 mm, 114,9 mm and 32.8 mm respectively. The errors of measurement (expressed as the error of the individual measurement) were calculated from the double determinations and were found to be 0.5 mm, 0.7 mm and 0.3 mm, respectively. The difference between total diameter and muscle diameter, and muscle diameter and bone diameter, were calculated individually in independent double determinations in the 30 cases, the mean figures obtained being 17.6 mm and 82.0 mm, respectively; the errors of the measurement were 0.8 mm and 1.1 mm, respectively.

Results

Blood flow. The *resting blood flow* in the amputation stump was somewhat higher than in the intact leg for patients in the age group 30–59 years. In the age groups below 30 years, on the other hand, the resting flow in the stump was as a rule lower than in the intact leg, and similarly in patients of 60 years and over (Table 12, Fig. 34 and 35).

	Age	Blood flow at rest ml/100 ml · min			Reactive hyperaemia max blood flow ml/100 ml · min			Reactive hyperaemia half-restitution time sec		
		n	M	r	n	M	r	n	M	r
Thigh below-knee amputees	10-29	5	4.5 (4.1)	3.3-7.0 (1.6-3.9)	2	26 (34)	16-36 (32-32)	2	90 (65)	80-100 (40-150)
	30-44	7	2.8 (2.7)	0.6-5.0 (1.3-4.3)	7	22 (20)	8-34 (9-38)	7	43 (57)	8-80 (30-100)
	45-59	6	2.7 (1.9)	1.1-4.5 (1.2-2.9)	5	12 (13)	14-23 (6-22)	5	63 (49)	35-100 (15- 90)
	60-68	6	1.9 (1.7)	0.6-2.9 (1.3-2.4)	4	9 (13)	2-16 (8-25)	4	55 (28)	20- 80 (22- 40)
	10-68	24	2.9 (2.5)	0.6-7.0 (1.2-4.3)	18	16 (18)	2-36 (6-38)	18	56 (53)	8-100 (15-150)
Calf below-knee amputees	10-29	7	2.1 (3.8)	1.1-2.8 (1.9-6.7)	2	9 (21)	8- 9 (19-23)	2	48 (75)	15- 80 (45-100)
	30-44	7	2.1 (1.9)	0.8-5.0 (0.5-3.4)	7	10 (30)	2-21 (15-51)	7	60 (59)	20-100 (20-120)
	45-59	7	2.9 (2.3)	1.1-7.1 (1.0-5.0)	6	17 (13)	6-41 (8-18)	6	72 (43)	10-140 (20-100)
	60-68	6	1.4 (1.6)	0.8-2.4 (1.0-2.2)	4	9 (14)	3-19 (1-22)	3	40 (>30)	10- 90 (15->15)
	10-68	27	2.2 (2.5)	0.8-7.1 (0.5-6.7)	19	12 (20)	2-41 (1-51)	18	59 (53)	10-140 (15-120)
Thigh above-knee amputees	16-29	5	3.0 (3.7)	1.1-6.4 (1.9-5.2)	4	6 (19)	4-10 (12-25)	4	65 (45)	4-90 (8- 80)
	30-44	6	3.1 (2.2)	1.2-5.0 (1.1-2.9)	5	18 (27)	2-39 (6-50)	5	44 (43)	25-65 (12- 75)
	45-59	8	2.7 (2.0)	0.8-9.3 (1.0-3.4)	3	17 (7)	4-37 (7-20)	3	28 (41)	8-40 (8- 95)
	60-72	1	0.8 (1.3)	-	1	5 (1)	-	0	-	-
	16-72	20	2.6 (2.4)	0.8-9.3 (1.0-5.2)	13	13 (19)	2-39 (6-50)	12	44 (47)	4-90 (8- 95)

Table 12. The table shows the blood flows in different age groups at time of examination, n = number, M = average value, r = range. The figures in brackets refer to the intact leg.

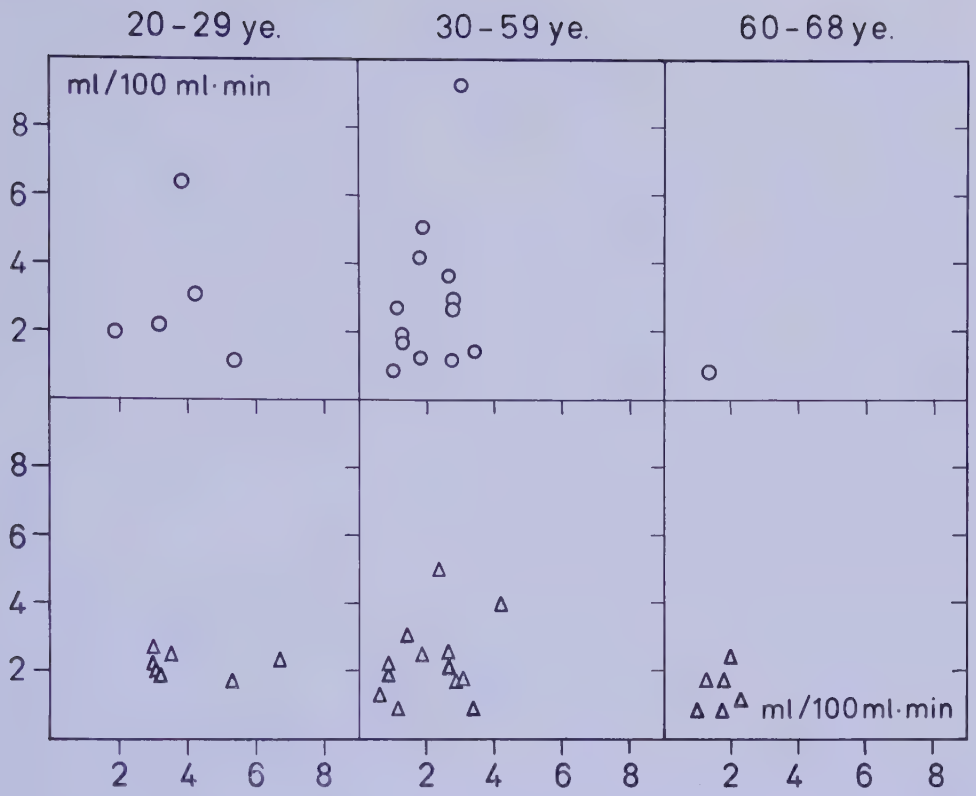


Fig. 34. The figure shows the blood flow at rest of above-knee (○) and below-knee amputees (△) classified into 3 age groups at time of examination. The values for stumps are given on the ordinate and the values for intact legs on the abscissa.

			Blood flow at rest ml/100 ml · min			Reactive hyperaemia max blood flow ml/100 ml · min			Reactive hyperaemia half-restitution time sec		
			n	age	M	n	age	M	n	age	M
Thigh below-knee amputees	Observ. time, years	0 - 2	4	36	3.5 (2.6)	3	39	16 (17)	2	45	65 (-)
		3 -10	16	44	3.0 (2.8)	12	43	17 (20)	12	43	59 (40)
		11 -49	5	50	2.3 (1.5)	4	49	16 (12)	4	49	34 (74)
Calf below-knee amputees	Observ. time, years	0 - 2	5	33	2.9 (3.1)	3	39	17 (26)	3	39	90 (50)
		3 -10	17	45	2.3 (2.5)	13	44	10 (19)	12	43	61 (57)
		11-49	5	50	1.6 (1.5)	4	49	9 (8)	4	49	48 (36)
Thigh above-knee amputees	Observ. time, years	0 - 2	5	34	2.3 (2.3)	4	38	28 (29)	4	38	33 (53)
		3 -10	10	42	3.1 (2.9)	6	33	12 (15)	6	33	54 (52)
		11-49	5	51	1.9 (1.8)	4	52	11 (16)	4	52	36 (23)

Table 13. The table shows blood flows at different times of observation. Symbols as in Table 12.

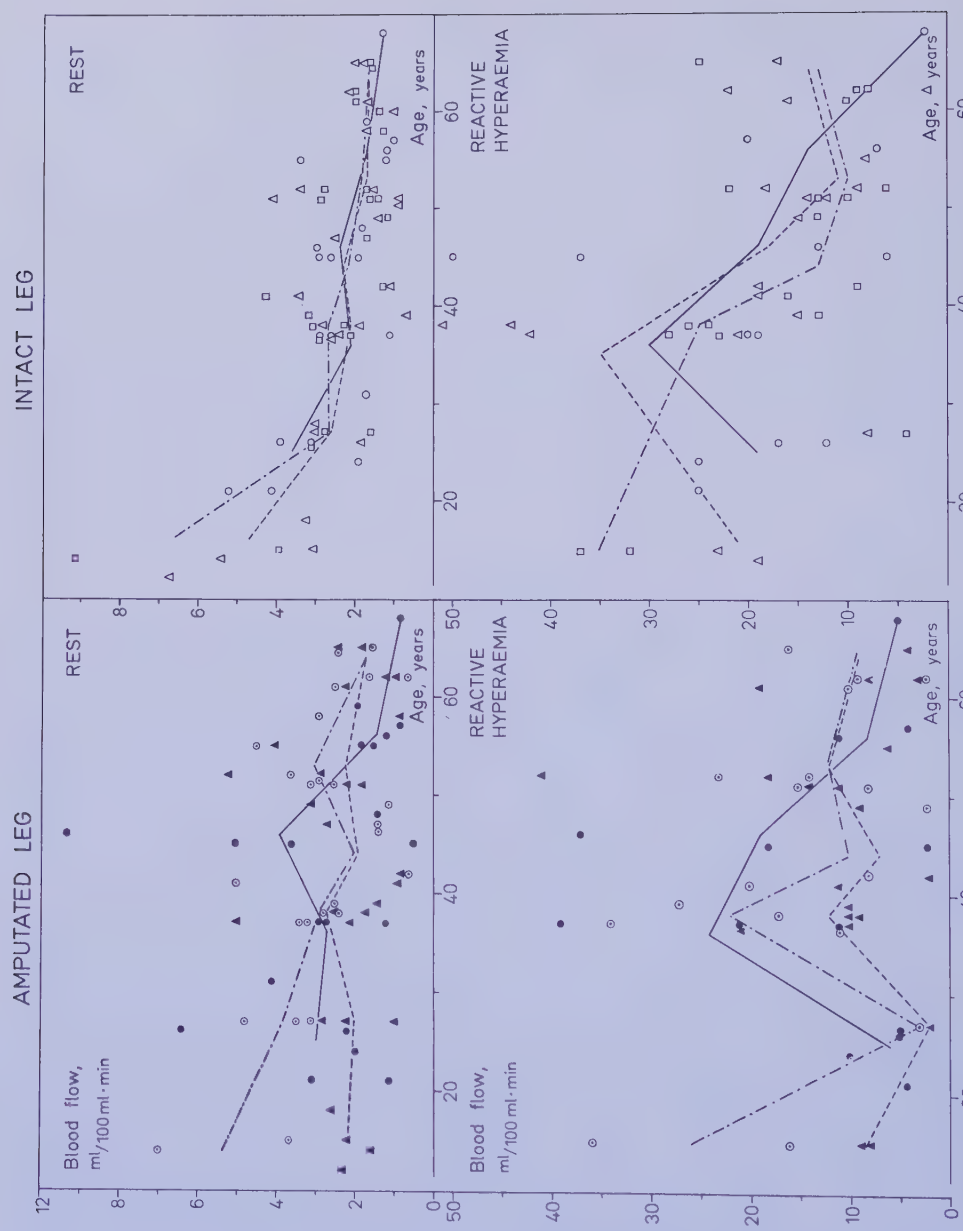


Fig. 35. The figure shows the blood flow at rest and maximum blood flow at reactive hyperemia at different ages at the time of investigation. ○ = intact thigh, above-knee amputees; □ and △ = intact thighs and calf of below-knee amputees respectively; ● = above-knee stumps; ▲ = below-knee stumps; ⊙ = thigh of below-knee amputated leg. The mean value for the blood flow and age for each decade are connected by ——— for the thigh of above-knee amputees, - - - - - - - for the calf and ·—·—·— for the thigh of below-knee amputees.

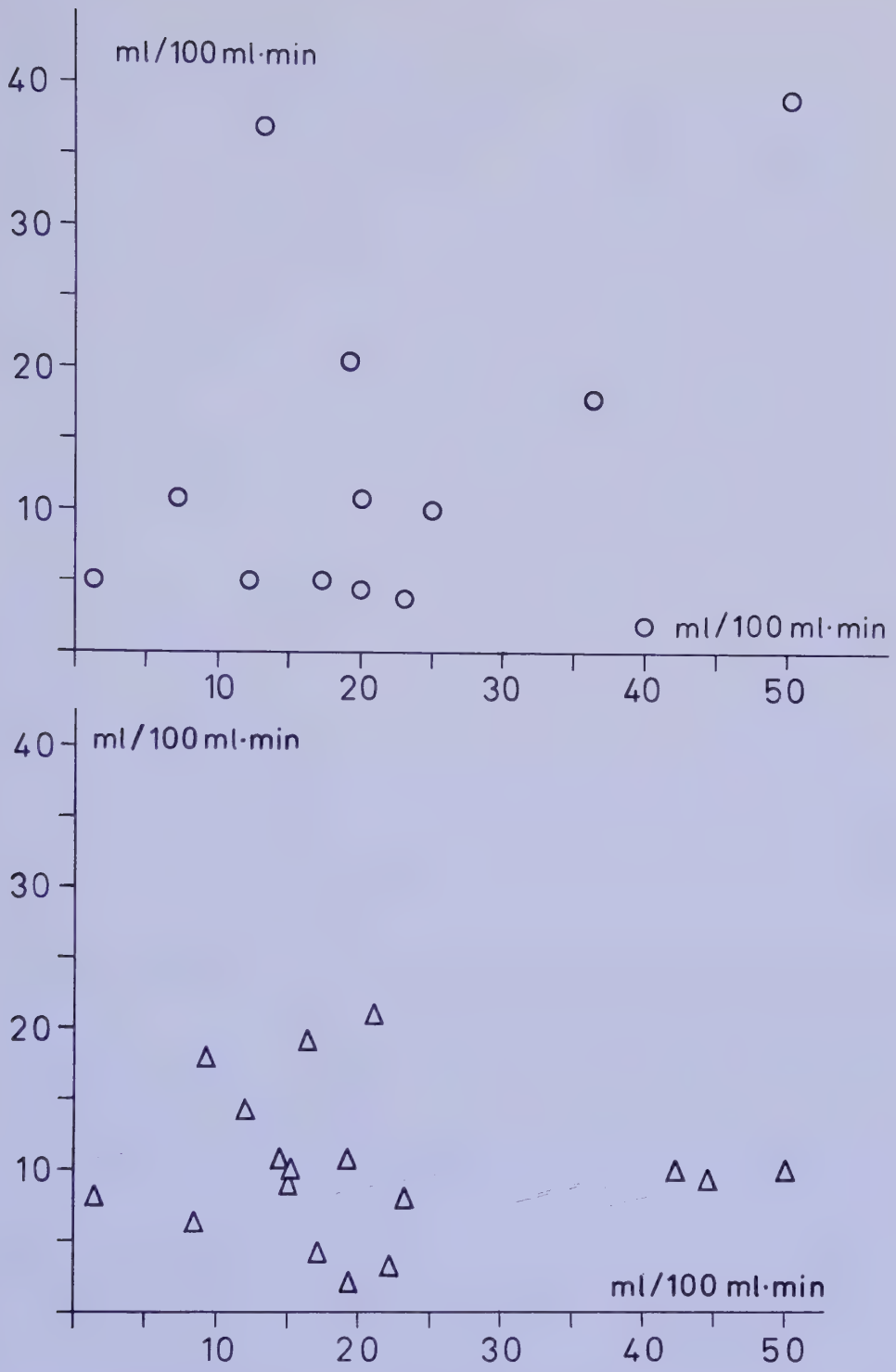


Fig. 36. The figure shows the maximum blood flow during reactive hyperemia in above-knee (○) and below-knee amputees (△). The values for the stumps are given on the ordinate and for intact legs on the abscissa.

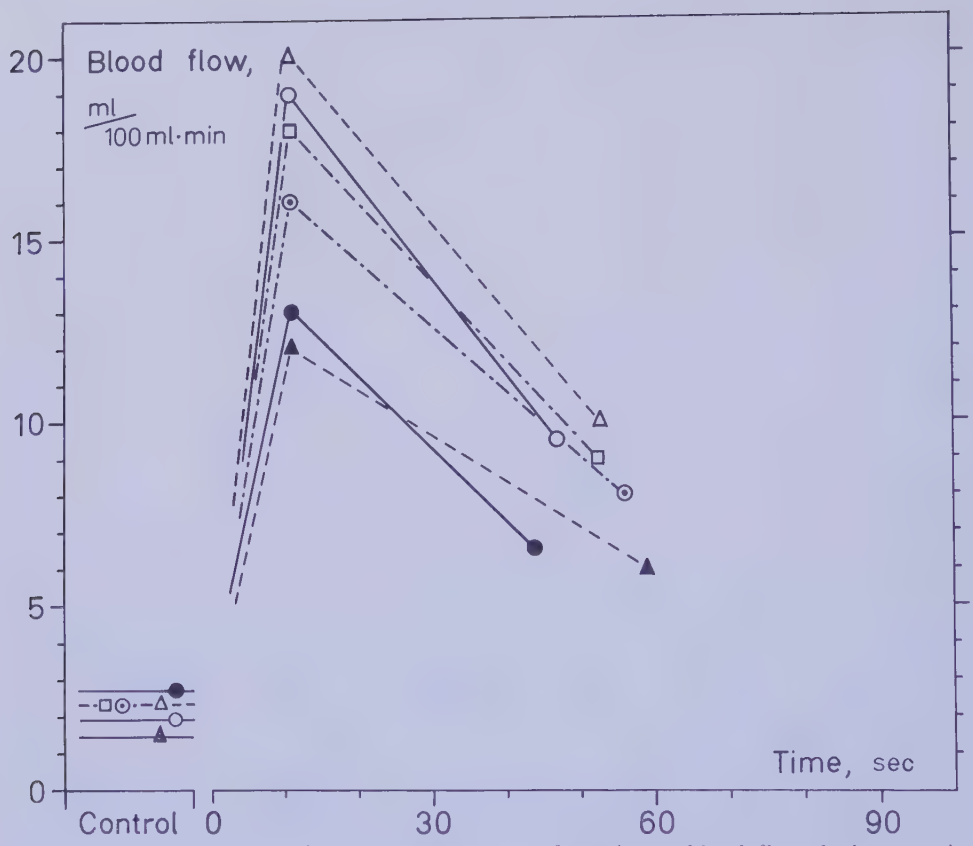


Fig. 37. The average value for all measurements of maximum blood flow during reactive hyperemia on different levels are shown. The same symbols as in Fig. 35.

In the lower leg amputees, in all age groups, the resting blood flow was on an average lower in the thigh of the intact leg than in that of the amputated leg. In the intact leg in both above- and below-knee amputees there was a tendency to a decrease in resting blood flow with increasing age (Fig. 34).

In both amputated and intact legs the blood flow at rest was lower in those cases with the longest observation times (Table 13).

The "*maximum*" *blood flow* measured during reactive hyperemia was on an average lower in the stump than in the intact leg (Fig. 36) and was reached bilaterally in an average of 11 seconds after release of arterial occlusion (Fig. 37). The maximal blood flow decreased somewhat as a rule with increasing age and increasing length of time after amputation (Tables 12 and 13, Fig. 35).

		Amputation stumps which are									
		warmer than intact leg					cooler than intact leg				
		v	m	d	l	M	v	m	d	l	M
BK	diff °C	+1.2	+1.1	+1.3	+0.9	+1.3	-1.3	-0.4	-1.6	-1.4	-0.8
	n	7	7	2	7	7	8	8	5	8	8
	r	0.4/2.3	0.1/2.3	0.6/2.0	0.6/2.5	0.4/1.9	-3.3/0.6	-2.9/0.2	-2.8/0.1	-3.4/0.2	-3.2/0.1
AK	diff °C	+0.7	+1.0	+0.9	+0.1	+0.5	-1.1	-0.8	-0.2	-1.6	-1.0
	n	3	3	1	3	3	13	12	13	13	13
	r	-0.7/1.5	-0.6/2.9	-	0.0/0.1	0.1/0.7	-3.5/0.5	-1.7/0.5	-0.9/1.1	-3.1/-0.3	-2.1/-0.3

Table 14. Difference in skin temperature between amputation stump and corresponding part of intact leg. Value in °C. Site of measurement in the ventral (v), medial (m), dorsal (d) and lateral (l) part of the stump or intact leg. The mean of the measuring sites (M) is also given, as well as number of patients (n) with above-knee (AK) or below-knee (BK) amputation, and individual range of variation (r). The mean temperature of all BK stumps was 32.0°C (28.5–34.3) and of all AK stumps 31.2°C (29.7–33.5). The corresponding mean temperatures of the intact legs were 32.0°C (29.9–33.5) and 32.1°C (30.4–33.6), respectively.

Type of amputation	Resting blood flow of stumps compared with that of intact legs	Amputation stumps which are	
		cooler than the intact leg	warmer than the intact leg
AK	high	5	2
	low	6	1
	equal	2	-
BK	high	2	3
	low	5	4
	equal	1	-
AK + BK	total	21	10

Table 15. The number of cool and warm stumps is given and comparison is made with the blood flow at rest.

Skin temperature. The results of the skin temperature measurements are given in Tables 14 and 15. In the below-knee amputees the average skin temperature was identical for the stump and the contralateral intact calf. In the above-knee amputees a small average difference was found, the stump being 0.9° C cooler than the intact thigh (Table 14). For the whole material, the stump was cooler in about 2/3 of the cases, but there was no apparent tendency to a lower stump blood flow in these cases (Table 15 and Figures 38 and 39).

Tissue proportions. The results of analyses of the tissue proportions with a soft tissue roentgen technique on the stump and intact leg showed

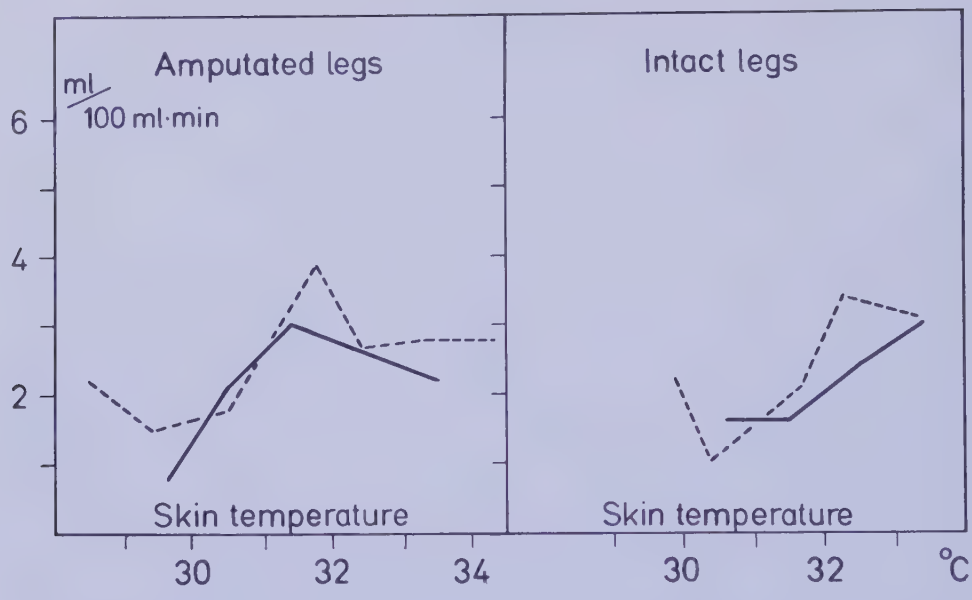


Fig. 38. The figure shows the average value for the blood flow at rest related to the average temperature for every degree between 28° and 34° C. Above-knee amputees are connected by ———— and below-knee amputees by - - - - - - - -.

that the proportion of muscular tissue in the amputation stumps was smaller than in the intact legs at a level with the site of the plethysmography cuffs, in all below-knee amputees and in all above-knee amputees except one (Table 16). The men and women had different tissue proportions, and different types of measuring cuffs enclosed different proportions of tissue. Fig. 40.

In the male above- and below-knee amputees the proportions of muscle in the intact thigh were about 74 % and 71 %, respectively, and in the male below-knee amputees the muscle proportion in the intact calf was about 77 % when the tissue corresponding to the site of the segmental cuffs was measured.

In one female above-knee amputee and 3 female below-knee amputees the proportions of muscle in the thigh of the intact leg were 67 % and 56 %, respectively, and in 3 female below-knee amputees the muscle proportion in the intact calf was 62 % when the tissue beneath the segmental cuff was measured.

In the men the proportions of muscle in the above- and below-knee stumps were 60 % and 50 % respectively when the tissue at a level with the segmental cuff was measured; in the women this value in the below-knee stumps

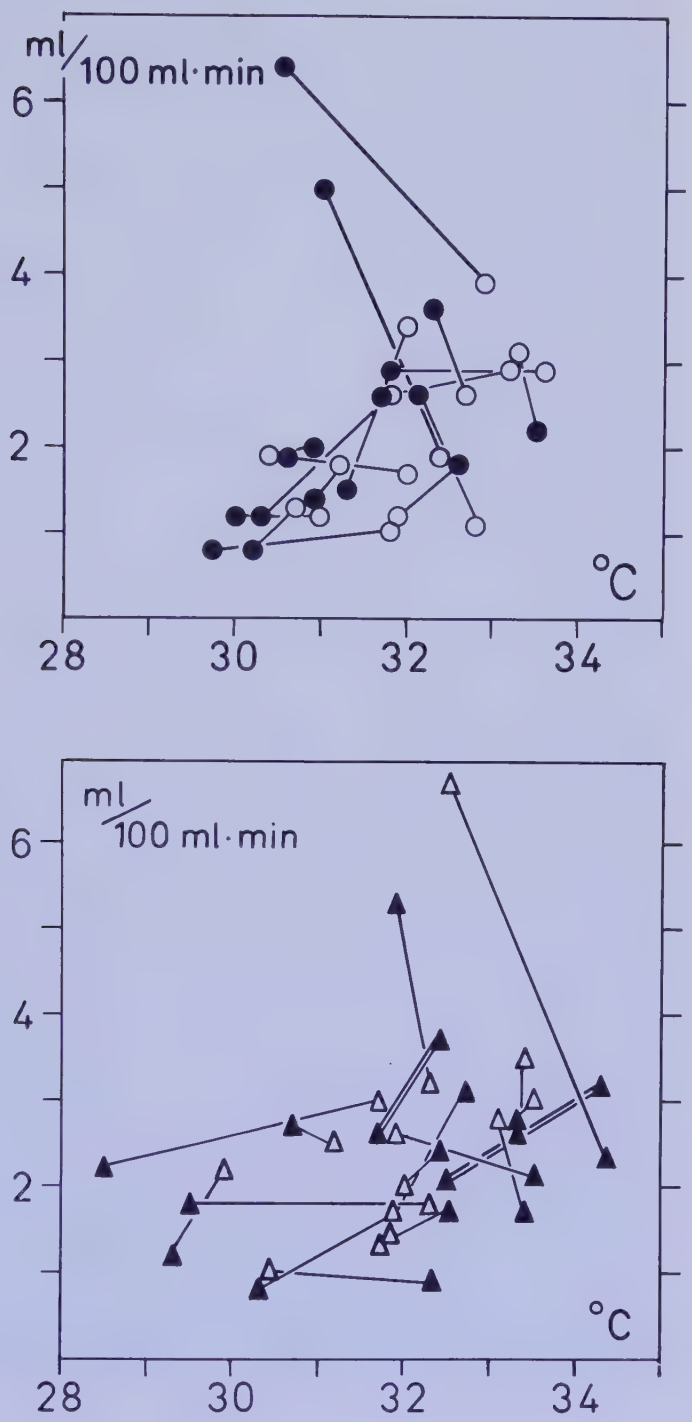


Fig. 39. The blood flow at rest in relation to the skin temperature in above-knee amputees (the upper figure) and below-knee amputees (the lower figure). Above-knee stumps (●), intact thighs (○), below-knee stumps (▲) and intact calves (△) of the respective patients are connected by a line. Double lines connect bilateral amputees.

Type of amputation		Type of cuff at plethysmography			Amputated leg			Intact leg		
					Skin %	Muscle %	Bone %	Skin %	Muscle %	Bone %
AK		Segmental	m	M	35	60	5	20	74	6
				n	11	11	11	10	10	10
				r	15-78	22-80	0-10	16-38	58-84	2-19
		bag	m + f	M	63	32	5	27	69	4
				n	5	5	5	5	5	5
				r	53-90	10-41	1-10	16-37	57-78	3-6
		bag	m	M	56	39	5	21	74	5
				n	4	4	4	4	4	4
				r	53-61	35-41	4-10	18-37	57-78	3-6
		bag	m	M	90	10	1	29	67	4
				n	1	1	1	1	1	1
				r	-	-	-	-	-	-
BK	thigh	segmental	m + f	M	27	66	7	27	67	6
				n	16	16	16	12	12	12
				r	15-51	43-79	3-13	10-49	46-87	3-11
	calf			M	36	50	14	20	73	7
				n	16	16	16	12	12	12
				r	18-56	19-74	2-25	10-38	57-82	4-11
	thigh	segmental	m	M	25	69	6	23	71	6
				n	13	13	13	9	9	9
				r	15-47	46-79	3-13	10-36	53-87	3-11
	calf			M	35	50	15	16	77	7
				n	13	13	13	9	9	9
				r	18-56	19-74	6-25	10-23	72-82	5-11
	thigh	segmental	f	M	32	58	10	40	56	4
				n	3	3	3	3	3	3
				r	26-51	43-69	5-9	31-49	46-63	3-6
	calf			M	46	54	6	33	62	5
				n	3	3	3	3	3	3
				r	30-48	40-65	2-12	29-38	57-70	4-6

Table 16. The table shows percentage of skin, muscle and bone in intact and amputated legs of above-knee (AK) and below-knee amputees (BK). For BK amputees figures are given for thigh and calf. All figures represent the tissue at the level of the plethysmographic cuff, i.e. the segment of which the blood flow has been measured. The bag type encloses more skin than the other type. M = mean value, N = number, r = range, m = male and f = female patient.

was about 54 %. These cuffs were not used on the amputated leg in any female above-knee amputee.

In 4 male above-knee amputees a bag-cuff was used in blood flow measurements on the stump, and the muscle proportion in the tissue enclosed by the cuff was about 39 %. In the intact thigh where a segmental cuff was used the corresponding value was 74 %.

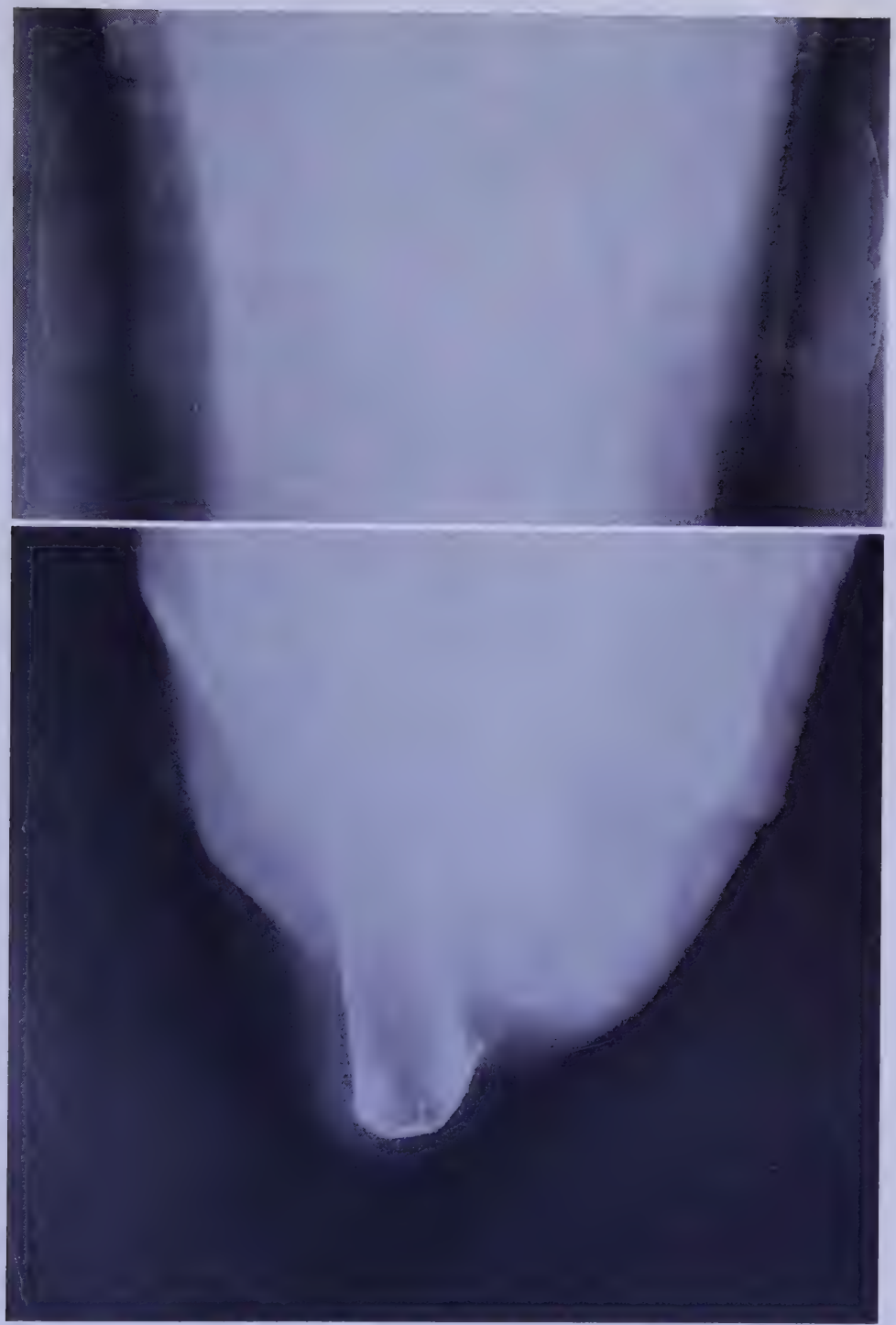


Fig. 40. The upper roentgenogram shows a segmental cuff and the lower a bag cuff.

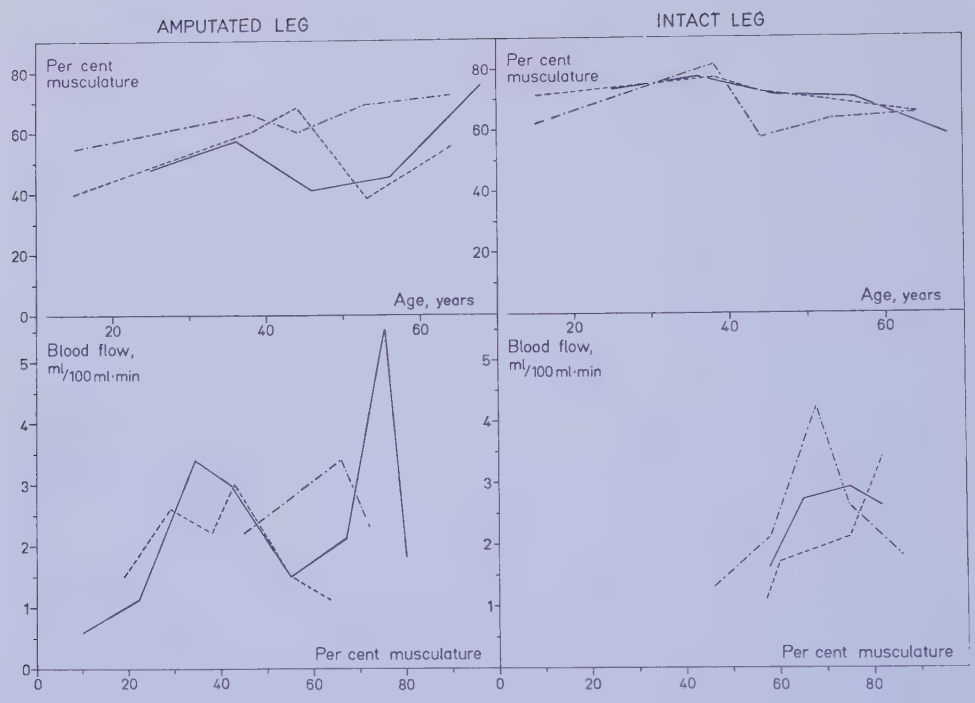


Fig. 41. (I) The relationship between the average percentage values for proportion of muscle tissue and the average age at the time of examination for each decade. (Upper curves.) (II) The relationship between the average values for blood flow at rest and the average percentage value of muscle tissue in the leg. The latter values are the averages for each 10 per cent range i. e. 10–19, 20–29 per cent etc.
For the lines see Fig. 35.

In 1 female above-knee amputee a bag-cuff was used in the investigation of the stump, and a segmental cuff on the intact thigh, and the proportions of muscle were 10 % and 67 %, respectively.

Muscle proportions at different ages. The muscle proportion in the stumps where segmental cuffs were used was somewhat higher in the higher age groups than in the lower (Fig. 41). In the oldest patient, who was a 68-year old above-knee amputee, the proportion of muscle in the stump was calculated as 80 %, and in the intact leg at the same level as 58 %. This

patient was the only amputee in whom the muscle proportion was found to be higher in the stump than in the intact leg.

In the intact legs there was possibly a tendency to a decreased muscle proportion in the higher age groups.

Relationship between muscle proportion and resting blood flow. The blood flow at rest and the muscle proportion in the intact leg were correlated, and a tendency to a higher blood flow with higher percentages of muscle tissue was observed (Fig. 41).

Corresponding comparisons in the amputation stumps did not show the same tendency with regard to the lower leg stumps, where on the other hand the blood flow was high even with relatively low muscle proportions. Similarly in the thigh stumps the resting blood flow was relatively high with lower muscle proportions but showed a tendency to an increase with higher muscle proportions.

Discussion

Blood flow and method of measurement. In evaluating the results of the blood flow measurements at rest and during reactive hyperemia consideration should be taken of the proportions of tissues enclosed by the measuring cuffs. It cannot be assumed that one particular segment of an extremity is comparable as regards the relative quantity of skin with its subcutaneous tissues and musculature, with a corresponding segment in the extremity of another person. The physiological status of the different tissues and their vascular anatomy must be considered. Furthermore the age of the subject plays a role; for example there appears to be a reduction of the resting blood flow with increasing age, which has also been shown in the present experiments (Fig. 34). Hellon & Clarke (1959), on the other hand, found in an investigation on healthy persons that the resting blood flow in the arm increases with age, while Allwood (1958) found no significant change in the blood flow of the calf with increasing age. His series consisted of older patients and may have included persons with vascular disease, which would seem to be indicated by the absence of a pulse in the dorsalis pedis artery in 7 cases out of 20. These patients were not investigated angiographically.

The investigation method with occlusion plethysmography is based on the

Fig. 42. 26611/62. Intraosseous phlebography in a below-knee stump. The injected contrast medium passes from the medulla to the superficial veins in the stump, showing open pathways. The same patient as in Fig. 8, chapter II.

assumption that the volume increase measured per time unit is identical with the arterial flow. Landowne & Katz (1942), in their critical study of plethysmography, stressed the importance of an arterial occlusion cuff distal to the measuring cuff. Graf (1964) also came to the same conclusion. They maintained that without occlusion increased flow could be obtained in certain cases, especially after warming. These authors used arterial occlusion on the intact leg distal to the measuring cuff.

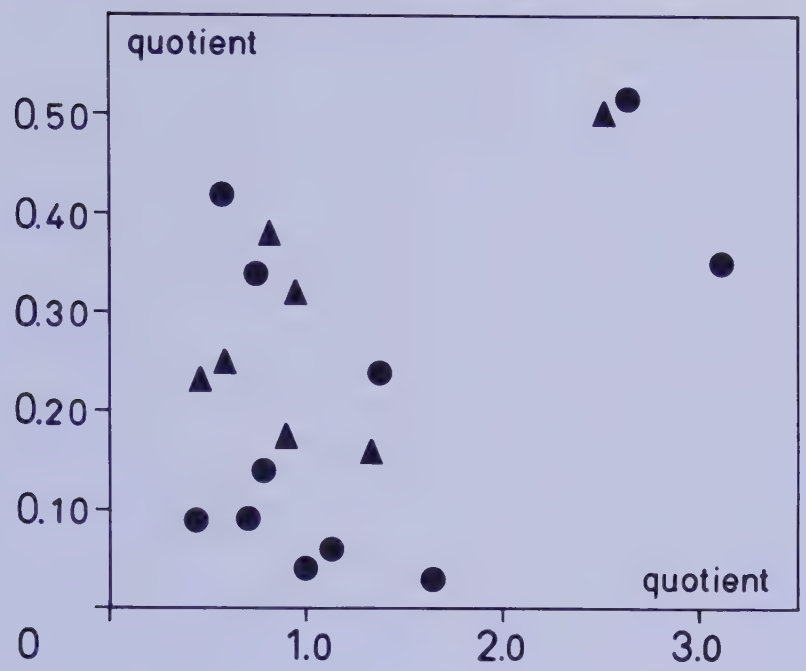


Fig. 43. Relationship between the quotient of the blood flow in amputated and intact legs, obtained by the roentgenological method (ordinate) and by plethysmography (abscissa), for above-knee ● and below-knee ▲ amputees.

No distal occlusion cuff was used on the amputation stump since the measuring cuff was placed as far distally as possible. On an intact leg the blood flow value would have been erroneously high in this situation because of the venous return in the skin from the foot. This cause of an error of measurement obviously does not arise in the case of amputated legs. High values for the flow in an amputation stump must thus be due to other factors, e.g. vascular changes, either anatomical or physiological. It should be taken into consideration that to a certain extent during the venous occlusion the blood, instead of filling the veins under the measuring cuff, may be shunted via the medullary canal (Shaw, 1963). Hulth & Olerud (1962) have shown in animals a communication between the medullary canal and a rich venous network in the distal amputation stump. Similar conditions may also be found in man (Fig. 42) but no study has been made here of the venous system in the amputation stump in man from this aspect. The blood flows measured in the amputation stump may thus be regarded as minimum values. A comparison was made between the roentgenologically

evaluated "blood flow" according to the results in chapter III and the blood flow at rest measured by plethysmography (Fig. 43).

For the below-knee amputees there may be some correlation between the two methods but for above-knee amputees it is not probable perhaps because of reasons already discussed in chapter III.

The maximum blood flow during reactive hyperemia following 8 minutes' arterial circulatory arrest in lower in the stumps than in the intact legs. Some authors, e.g. Landowne & Katz (1942) and Carlsten & Thulesius (1962) claim that the anatomical dimensions of the arteries constitute the restricting factor in reactive hyperemia. This postulation may explain the present result during reactive hyperemia as arising from the fact that the dimensions of the main arteries of a stump are smaller than those of an intact leg (see chapter III).

Skin temperature and blood flow. The results of the blood flow measurements may be compared with Loon's findings mentioned previously. This author considered that the usual coldness of the amputation stumps indicated a reduction in peripheral blood flow.

When the body is cooled the temperature of the fingers falls rapidly and the skin temperature of the forearm also drops progressively. When the body is warmed the venous return from the hand not only modifies but is also a principal factor controlling the temperature of the forearm skin. "The warming and slight flushing of forearm skin that occur when the body is warmed are due entirely to the venous return from the hand" (Grant & Pearson, 1937); these authors also claimed that in the intact leg, too, the arteriovenous anastomoses of the foot played an important part in regulating the temperature of the skin. They also showed that direct conduction of heat from active muscles in an important factor in warming the overlying skin. When studying the effect on stump temperature of warming the body of amputees one must remember that no warm blood can come from the arteriovenous anastomoses of the foot and also that the muscle mass is reduced and the skin proportionately increased. It may therefore be erroneous to conclude from temperature studies of the skin that the blood flow in the central parts of the stumps is decreased.

It was shown on the contrary in the present investigation that in many patients the blood flow at rest per tissue volume in the stump is higher than in the intact leg despite the fact that the stump is cooler.

The results from the temperature measurements show that out of 31 patients 10 had a higher mean temperature on the skin of the stump in comparison with the intact leg. A possible explanation for this finding, apart from an increased arterial blood flow in the muscles, may be arteriovenous anastomoses which shunt the relatively warm blood of the muscle to the

venous system of the skin. This is illustrated by Fig. 13 in chapter II, which shows an arteriography from a below-knee amputee whose stump skin temperature was 1.8° C higher than the skin temperature in the intact leg, and in whom an arteriovenous anastomosis is seen in the stump. The resting blood flow measured in ml/100 ml · min was 2.3 in the stump and 6.7 in the intact leg.

Proportions of muscle tissue and blood flow at rest. The proportion of muscle in an intact leg was relatively constant but showed a tendency to decrease with increasing age. In the amputated leg there was possibly a tendency to an increase with age. In an amputation stump, because of atrophy after the operation, there is a total volume decrease by about 30 %, which is evident from the relationships between the volumes under the measuring cuffs placed at the same level. The muscle volume, however, appeared to decrease to a higher extent than the total volume. In the majority of patients in the present series, as in those reported by Loon, the amputation stumps were cold, which should indicate a low blood flow through the skin. If this skin blood flow is lower than the muscular blood flow the relatively high resting blood flow values obtained in certain amputation stumps may indicate an increased muscular blood flow as compared with the intact leg.

Summary

1. The segmental blood flow at rest, measured by venous occlusion plethysmography, was higher in the majority of stumps than in the corresponding segment of the intact legs.

2. The maximum blood flow during reactive hyperemia was lower in the stump than in the intact leg.

3. The average skin temperature of the stump was lower than that of the intact leg in the above-knee amputees but identical in the below-knee cases.

4. A lower skin temperature on some of the stumps compared with the intact leg does not indicate a lower resting blood flow.

5. The proportions of different leg tissues were measured by means of roentgen technique. The proportion of muscle was variable, and in general was lower in the stump than in the intact leg.

6. There was a tendency to higher blood flow at rest with a higher muscle proportion in the intact leg. In the stump this tendency was not apparent; the blood flow at rest was in many cases high in spite of a low muscle proportion.

CHAPTER V

Effect of close arterial infusion of certain vasoactive drugs on blood flow and angiographic picture

The appearance of the vessels and their distribution in the amputation stumps varied, as pointed out in chapter II, different degrees of tortuosity and vascular richness being observed. Their mode of reaction to vasoactive substances was tested in order to determine whether there was any change in function in the arterial network, in particular. Possible effects of vasoactive substances on pain in the stump were also studied.

The effects of some known vasoactive substances, viz. bradykinin, acetylcholine, histamine, ATP and noradrenaline were investigated in a number of patients. These agents were administered arterially both in the stump and the intact leg, and their effects were studied by arteriography and plethysmography, i.e. the anatomy and function of the arteries and in some cases the veins were examined during different experimental situations. No similar study on amputation stumps appears to have been made previously.

Vessel-dilating media have been used previously in order to increase the degree of anatomical information obtained in arteriographies on legs (Wickbom & Bartley, 1957 and Vogler, 1954, among others). The latter author claimed also to have obtained, from arteriographies, pathophysiological data concerning the function of arteriovenous anastomoses in patients with varices and leg ulcers.

In a previous publication the author reported the effects of bradykinin, acetylcholine and histamine used in connection with arteriographies on a series of amputees and also patients with intact legs but suffering from different vascular diseases. It was found that by using bradykinin in particular, with its dilating effect, more information on the arterial anatomy was obtained (Erikson, 1965).

Methods and material of patients

Arteriography. The same apparatus and catheter technique were used as described in chapter II. The arteriographies were performed partly without any preceding intra-arterial injection of a vasoactive drug, and partly after such an injection.

Site of amputation	Bradykinin, µg/min					Acetylcholine, mg/min					Histamine, µg/min		Noradrenaline, µg/min		ATP mg/min
	2	4	6	8	20	2	5	10	12.5	28	7	10	2.5	5	28
Above knee	1	2	6	3	1[x)]	1	2[x)]	7	1	1	1	8	1	1	
Below knee		1	5	3			2[x)]	2		1	1	3	1[x)]		1

Table 17. No of patients with AK and BK amputation, investigated with intraarterial continuous injection of different vasoactive drugs at different dose rates. In most cases the tip of the catheter was placed in the femoral artery: the numbers marked* each contain one patient where the catheter tip was placed in the abdominal aorta.

Above-knee amputees. In 14 above-knee amputees arteriography was performed after the injection of drugs. In 2 patients the catheters were introduced bilaterally via the femoral artery to a level of about 6–8 cm above the aortic bifurcation. Contrast medium was injected through one of the catheters and a drug through the other. In the remaining 12 patients the catheters were introduced into the inguinal part of the femoral artery about 6 cm above the puncture site (Table 17).

Below-knee amputees. In 1 patient the catheter was introduced to a level of 6 cm up the aorta and in 10 patients to a level of 6 cm above the site of puncture in the inguinal part of the femoral artery (Table 17).

Arterial diameters and rate of contrast passage. The diameters and rate of movement of the contrast medium were measured on the arteriogram, performed with or without the influence of drugs, in the same way as described in chapter III.

Plethysmography. The apparatus, method and conditions were the same as described in chapter IV. The doses used and their sites of injection are given in Tables 21–25.

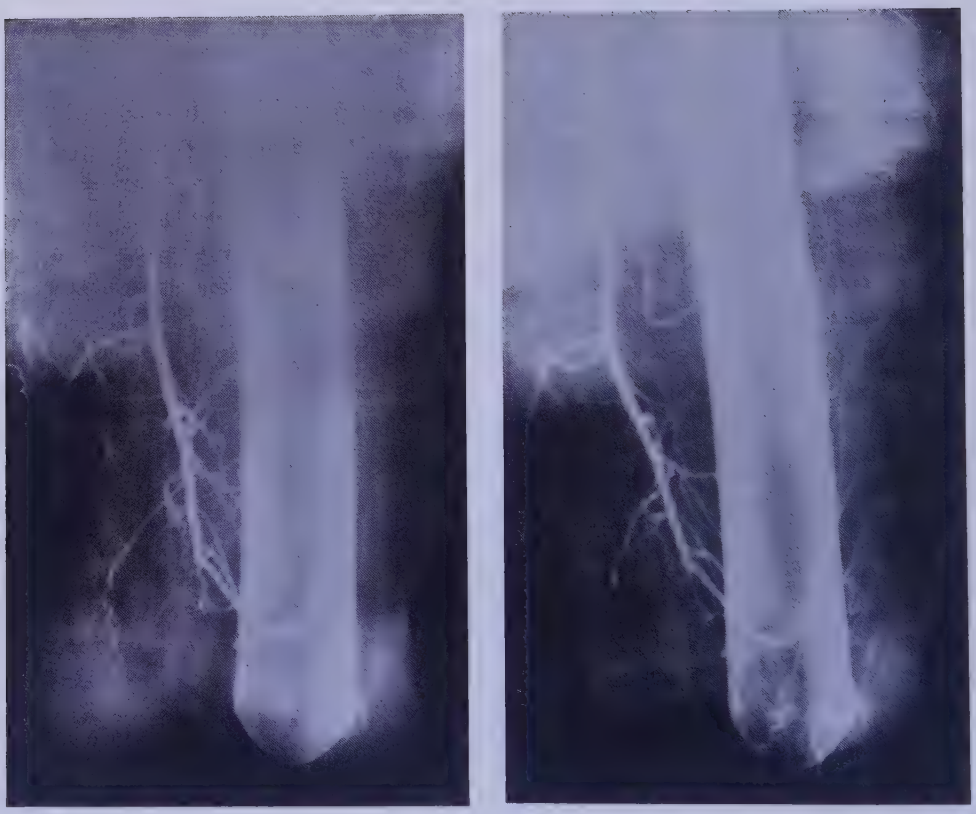
Substances investigated. 1. *Bradykinin* (Sandoz) was obtained in ampoules of 0.1 g in 1 ml 0.9 % NaCl. A solution of 0.4 mg bradykinin in 100 ml 0.9 % NaCl was prepared. The concentration was 4 µg/ml.

2. *Acetylcholine* (Roche). 280 mg of dry substance were dissolved in 100 ml 0.9 % NaCl. The concentration was 2.8 mg/ml.

3. *Histamine* (ACO). Ampoules of 1.0 mg. A solution of 200 µg in 100 ml 0.9 % NaCl was prepared. The concentration was 2 µg/ml.

4. *ATP* (adenosine-3-triphosphate, Kebo). Ampoules of 1 g. These were dissolved in 100 ml 0.9 % NaCl. The concentration was 10 mg/ml.

5. *Noradrenaline* (Nor-exadrine, Astra). Ampoules of 1 ml with 5 µg. 10 ampoules were dissolved in 100 ml 0.9 % NaCl. The concentration was 0.5 µg/ml.



a b

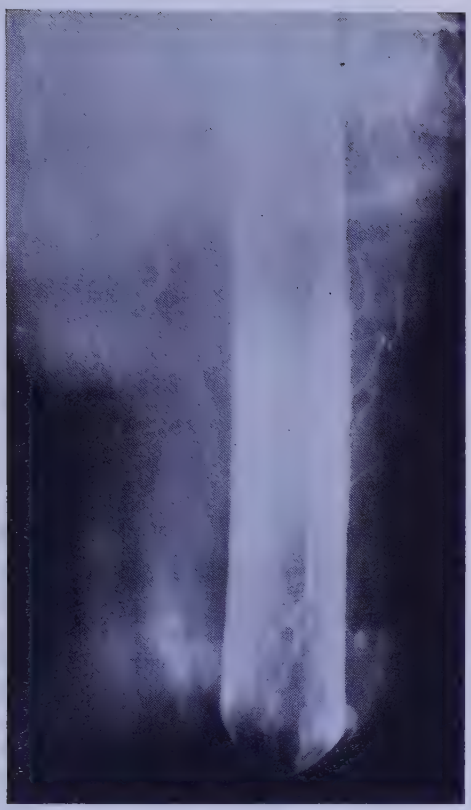
Fig. 44. (15639/62) Male above-knee amputee 47 years old, amputated 9 years ago because of trauma. a) Arteriography without drugs; b) Arteriography after bradykinin; note increased contrast-filled arteries in the stump; c) Arteriography after acetylcholine; note

6. Atropine (ACO). Ampoules of 0.5 mg/ml.

All solutions nos. 1–5 were prepared immediately prior to the investigation and were injected through catheters into the femoral artery by means of an automatic apparatus which allowed different rates of injection. Atropine was given as a single dose, by hand through the arterial catheter.

Procedure

The patient lay on an examination table throughout the investigation and was asked to be as calm and relaxed as possible. He rested for about 30 minutes after the catheter had been introduced and the plethysmography



c

d

the poor contrast filling in the region of the superficial femoral artery; d) Arteriography after histamine; note the increased contrast filling of the arteries. The segmental cuff used for plethysmography is visible.

apparatus applied. The resting blood flow was then determined by plethysmography, after which arteriography was carried out on both legs. The increase in blood flow which was regularly caused by arteriography lasted for only 2–3 minutes, but as a safety precaution the next stage of the investigation was not performed until about 30 minutes had elapsed. During this period the resting blood flow was checked and when it had returned to and remained constant at the original value the first series of intra-arterial injections of drugs was commenced. Each injection was given for 10 minutes. When the blood flow during the last, i. e. the highest dose in the series had been measured in both legs a new arteriography was performed, this time of the stump alone. With this the injection was discontinued and blood was allowed to pass backwards out through the catheter for a few seconds in

order to remove the remaining active substance. The syringe for the contrast injection was then connected and this was given (often by hand) over a period of 2–3 seconds. The minimum interval between the discontinuation of the drug injection and the commencement of the contrast injection was 4 seconds, and the maximum 10 seconds. After the second arteriography there was a further pause of 30 minutes during which time the resting blood flow was measured.

The infusion of *bradykinin* was given with different increasing rates of dosage. The lowest dose given to any patient was 0.5 μg/min and the highest 20 μg/min.

The *acetylcholine* was subsequently infused via the catheters in two dose rates of between 2 and 28 mg/min. The dose was determined by whether or not any discomfort had been sustained during the first acetylcholine injection (see below).

In a small number of patients the investigation was extended by a series of *histamine* injections, as a rule in two rates of dosage of between 2.5 and 10 μg/min, with measurement of the blood flow and a final arteriography of the stump.

In one below-knee amputee the investigation was complemented by an injection of *ATP* in a dose of 2.8 mg/min followed by a further arteriography of the stump.

26 patients were given one or more of these vasoactive substances. Arteriography and plethysmography were performed in 22 of them, arteriography alone in 3 of them, and plethysmography alone in 1 patient.

Results

A. Arteriographies

The effects of the vasoactive substances on the arteriography were assessed by comparison with the conventional arteriography, i. e. where no drug had been administered before the injection of contrast medium. Examples of the arteriographies are given in Figs. 44 and 45. These series of pictures show a similar form of reaction in both the above- and below-knee amputees. Schematically this may be described as an increased arterial filling in the distal part of the stump after bradykinin, decreased after acetylcholine and increased after histamine and in the single case with ATP. The results are shown in Table 18, which also gives the blood flows in those cases where they were measured by plethysmography immediately prior to an arteriography.

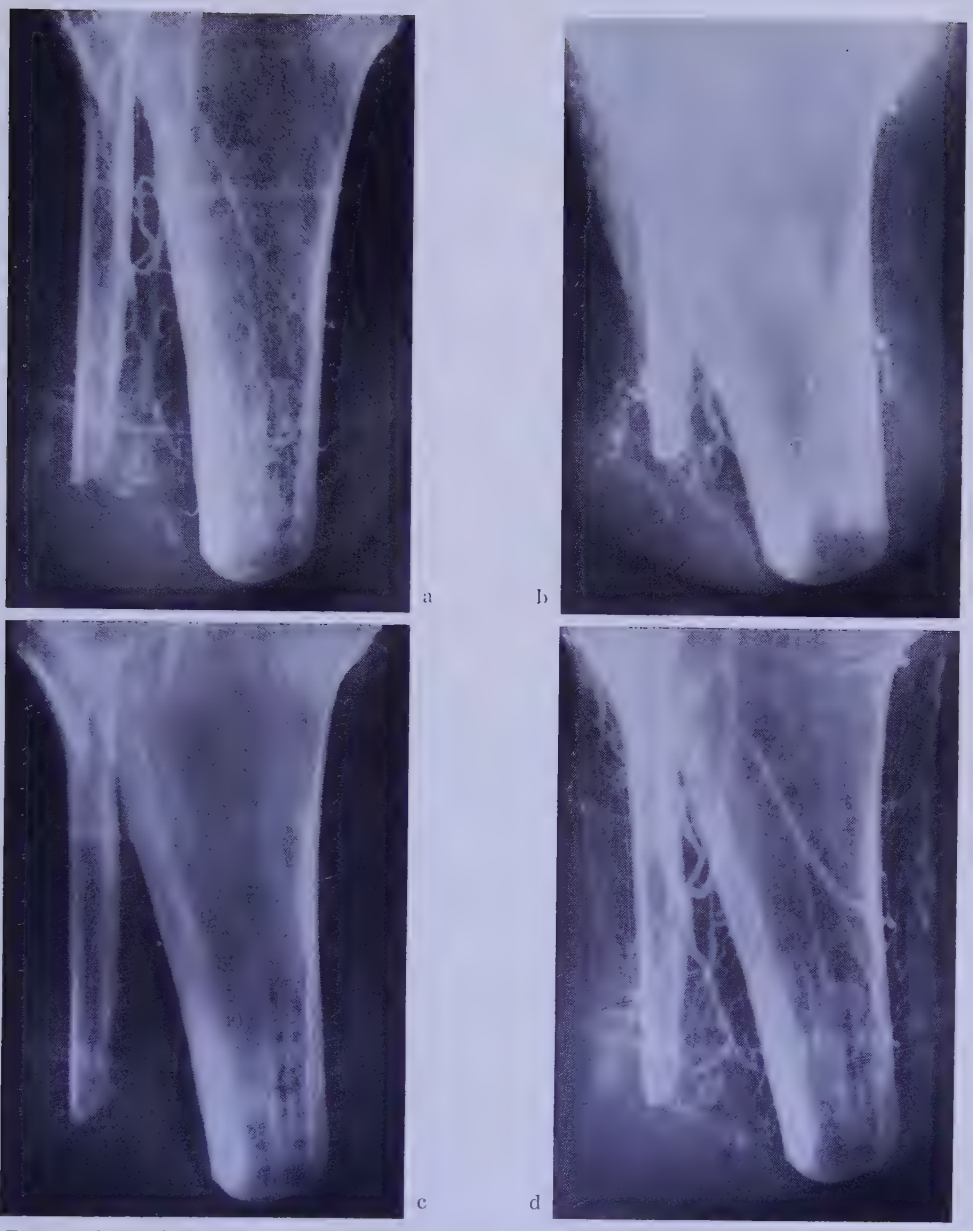


Fig. 45. (19006/62) Male below-knee amputee 26 years old amputated 6 years ago because of trauma. a) Arteriography without drugs; b) Arteriography after bradykinin; note the increase in contrast-filled arteries, some of which are spiralled (unsharpness because of intense pain of phantom type; see side effects and complications); c) Arteriography after acetylcholine; note the poor contrast filling in the stump; d) Arteriography after histamine; note increased contrast filling of the arteries. The segmental cuff used for plethysmography is visible.

Site of amputation		Blood flow at rest ml/min x 100 ml	Effects of bradykinin on arteriography					
			-		0		+	
			Dose µg/min.	Bf ml/ 100 ml. min.	Dose µg/min.	Bf ml/ 100 ml. min.	Dose µg/min.	Bf ml/ 100 ml. min.
AK	M	6.2			4.0	6.0	5.7	16.2
	n	8			1	1	11	7
	range	1.6-9.6			-	-	2.5-8	6.0-21.8
	M	1.8			20.0	2.6		
	n	1			1	1		
	range	-			-	-		
BK	M	2.1			7	5.0	6	8.5
	n	11			2	2	9	9
	range	0.8-3.6			6.8	0.8-9.1	4-8	3.1-22.2
	M	4.1						
	n	1						
	range	-						

Table 18. Effects of bradykinin, acetylcholine and histamine on the arteriography;—means reduced contrast filling of the arteries, 0 no change and + increased contrast filling of the arteries of the stump as compared with the arteriography performed without any

1. *Bradykinin.* Bradykinin gave an increased arterial filling in the amputation stumps in 20 of the 24 patients who received this drug. This was associated with a large increase in the blood flow recorded.

In 11 above-knee amputees there was an increase in the arterial filling in the stump after bradykinin injections given into the femoral artery in a mean dose of 5.7 µg/min. In 6 of these patients the superficial femoral artery and its distal branches in the stump filled with contrast considerably earlier than the deep femoral artery and its branches (Fig. 44 b). There was no distribution pattern such as this in the conventional arteriographies. The blood flow increased greatly in these 7 above-knee stumps. In one of them it increased almost tenfold when a dose of 2.5 µg/min was given.

In one above-knee amputee bradykinin was administered intra-aortally by means of a catheter introduced through the femoral artery in the intact leg. In this patient it was impossible to puncture the femoral artery on the amputated side since he had undergone a therapeutic resection of the superficial femoral artery and had large scars in the inguinal region. His stump was very short and the blood flow difficult to measure plethysmographically. In spite of relatively large doses of bradykinin (20 µg/min) no large increase of the blood flow was observed and neither was there any increase in vascular filling on arteriography. In one further leg stump the arteriogram and blood flow remained unaffected by the dose of bradykinin tested, i. e. 4 µg/min

Effects of acetylcholine on arteriography						Effects of histamine						Site of injection
-		0		+		-		0		+		
Dose mg/min.	Bf ml/ 100 ml. min.	Dose mg/min.	Bf ml/ 100 ml. min.	Dose mg/ min.	Bf ml/ 100 ml. min.	Dose µg/ min	Bf ml/ 100 ml. min.	Dose µg/ min.	Bf ml/ 100 ml. min.	Dose µg/ min	Bf ml/ 100 ml. min.	
9.7	10.5	7	15.4					10		9.5	15	A. femoralis
9	5	2	2					2		7	5	
2.8-28.0	4.8-15.6	5-10	3.8-21.9					10-10		7-10	8.3-27.1	
		5	13.8									Aorta
		1	1									
		-	-									
15.6	5.7									9	16.0	A. femoralis
5	5									5	4	
4-28	0.5-14.0									5-10	4.2-21.2	
		5	4.9									Aorta
		1	1									
		-	-									

preceding drug. M is the mean value, n the number of stumps investigated and BF the blood flow in ml/100 ml. min.

In 9 *below-knee* stumps a considerable increase in arterial filling in the stump was observed after bradykinin injections given at an average dose rate of 6 µg/min (Fig. 45 b). In two below-knee amputees the degree of filling was unchanged, i. e. no new vessels appeared (Table 18); the larger arteries were dilated, however, but not the smaller. In one of these below-knee amputees the investigation was repeated on a later occasion but gave the same result.

2. *Acetylcholine.* In 14 stumps out of 18 this resulted in a marked decrease in the contrast filling of the arteries (Table 18).

Acetylcholine was given to 12 *above-knee amputees.* In 9 patients who were given this drug into the femoral artery at an average dose rate of 9.7 mg/min a decrease in contrast filling was observed, this being shown primarily by the region supplied by the superficial femoral artery (Fig. 44 c). In 5 of these 9 patients the blood flow was recorded, and showed an increase of about 50 %. In 2 of the 12 above-knee amputees no change was seen in the contrast picture after the acetylcholine injection: the blood flow increase was more pronounced in these patients, and they had a relatively large area left of the superficial femoral artery, with long stumps in which the musculature was well retained distal to the bone stump. In one above-knee amputee acetylcholine was given into the aorta at a rate of 5 mg/min without any definite effect on the vascular picture, but with an increase in the blood flow.

		AK		BK Superficial femoral artery		
		Superf. femoral artery	Deep femoral artery	20 cm above knee joint	10 cm above knee joint	0 cm above knee joint
No drug	n	8	8	8	8	8
	M mm	3.5	3.2	5	4.5	3.5
	r mm	2.6-4.4	2.5-4.3	3.4-6.7	2.5-6.2	2.2-4.5
Bradykinin	n	8	7	8	8	8
	M mm	3.8	3.7	5.2	4.8	4.1
	-%	+12	+19	+5	+9	+17
Change of diameter in per cent of initial value	r mm	3.1-5.0	2.3-5.5	3.8-7.0	3.0-6.5	2.2-6.0
Acetylcholine	n	6	7	5	5	4
	M mm	4.4	4.4	6.5	6.0	4.0
Change of diameter in per cent of initial value	-%	+20	+33	+13	+13	+1
	r mm	3.6-5.8	3.6-5.5	5.5-8.0	4.0-6.5	2.5-5.0
Histamine	n	4	4	5	5	5
	M mm	4.1	3.5	5.7	5.4	5.0
Change of diameter in per cent of initial value	-%	+8	+7	0	0	+1
	r mm	2.8-5.0	3.0-4.0	4.7-6.5	3.5-7.0	3.1-5.0

Table 19. The diameters of the main arteries at different levels after action of different vasoactive drugs in above-knee (AK) and below-knee (BK) amputees. n is the number of stumps, M the mean, % the change of diameter in per cent of initial value and r the range of values.

Acetylcholine was given to 6 *below-knee amputees*. In 5 of them injection of this drug into the femoral artery at an average dose rate of about 15 mg/min resulted in a decrease in arterial filling with contrast. In 1 patient the vascular picture was unchanged after intra-aortal administration of 5 mg/min (Fig. 45 c).

The maximal doses of acetylcholine injected varied because of the reactions of a number of patients, with pain around the puncture site in the groin in some cases, and in 1 case vomiting. One male above-knee amputee, for example, tolerated only 2.8 mg/min, while a female above-knee amputee received 28 mg/min with no discomfort.

3. *Histamine*. In 7 out of 9 above-knee amputees and all of 5 below-knee amputees this drug resulted in an increase in arterial filling (Table 18). The mean dose given was 9,5 μg/min into the femoral artery (Fig. 44 d and 45 d).

4. *ATP*. ATP was given to one below-knee amputee at a dose rate of 2.8 mg/min; an increase in the blood flow in the stump was observed, and also some increase in arterial filling, but this was counteracted by a diluting effect which reduced the capacity of the contrast medium to enable detailed

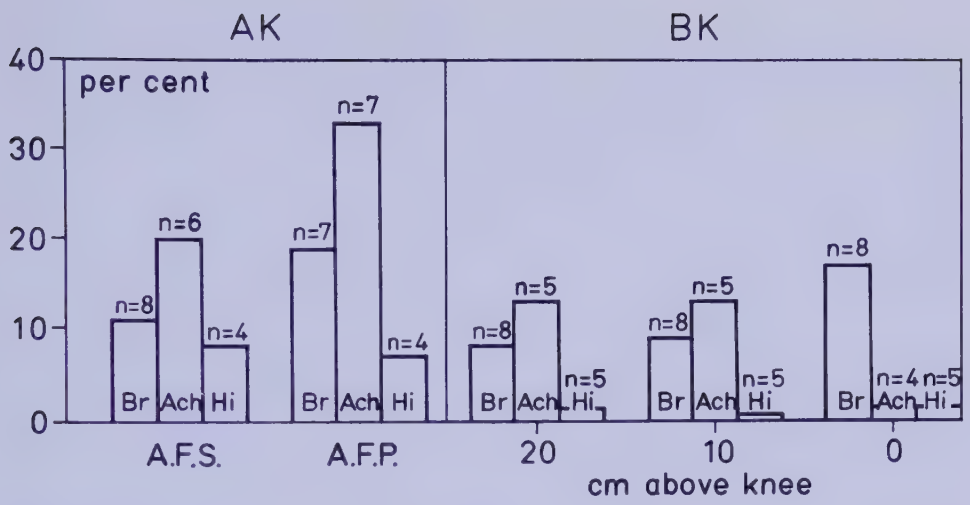


Fig. 46. The bars represent the mean change in the main arteries in per cent, measured in above-knee amputees (AK) in the superficial (AFS) and deep (AFP) femoral arteries, and in below-knee amputees (BK) in the superficial femoral and popliteal arteries, at three levels. n = no. of observations, Br = bradykinin, Ach = acetylcholine, Hi = histamine.

visualization of the arteries. No similar effect on the arteriographies was observed after administration of the other drugs.

5. *Noradrenaline.* In 2 above-knee amputees and 1 below-knee amputee the contrast filling was greatly decreased after injection of noradrenaline into the femoral artery and aorta respectively.

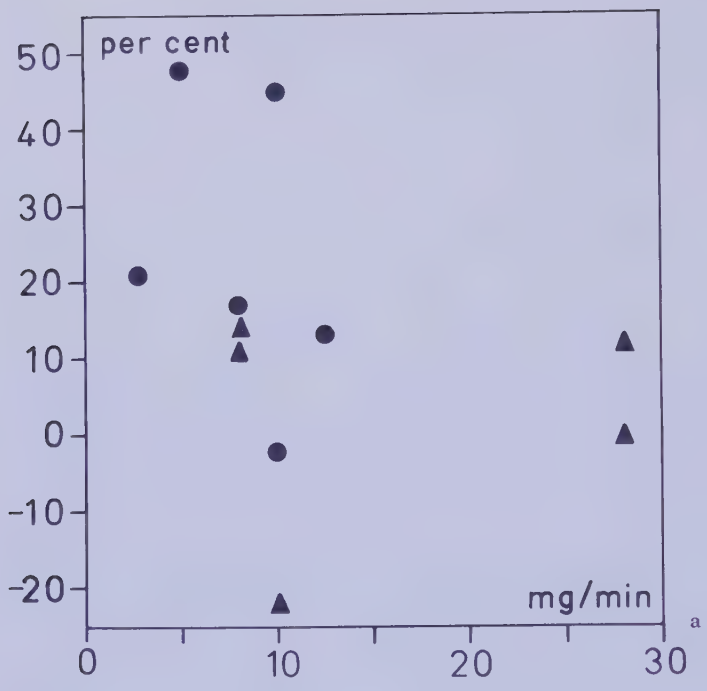
B. Arterial diameters

The diameters of the large arteries were increased arteriographically after the administration of bradykinin, acetylcholine, histamine and ATP, especially after acetylcholine (Table 19 and Fig. 46). On the other hand no distinct correlation was found between dose rate and degree of diametric change (Fig. 47).

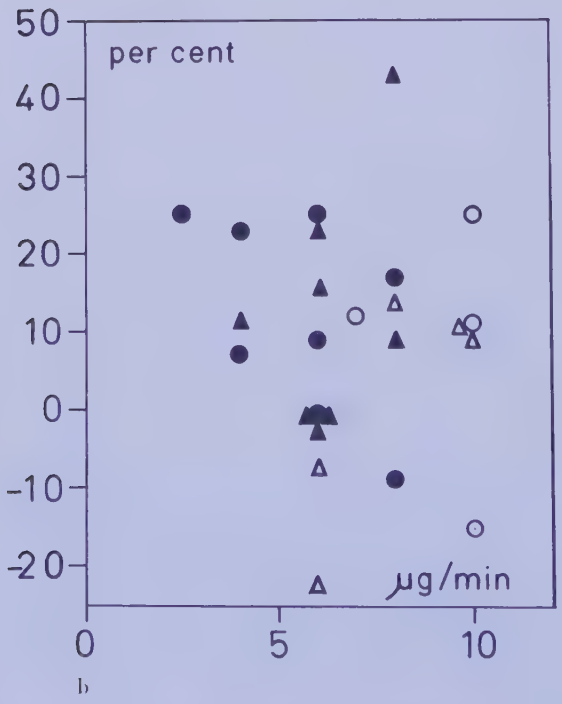
The arterial diameters were smaller after noradrenaline and at some levels impossible to measure.

Bradykinin. In 8 above-knee amputees the diameter of the superficial femoral artery was measured in the stump. In 6 of them the diameter had increased, in 1 it had decreased and in 1 it was unchanged after bradykinin. In 7 legs amputated above the knee the deep femoral artery was measured; in 6 of them it was increased and in 1 decreased.

In 8 legs amputated below the knee the diameters of the superficial



a



b

Fig. 47 a and b. The effect of acetylcholine (a) and of bradykinin (b) on the diameter of the superficial femoral artery in above-knee amputees, ●, and of the popliteal artery in below-knee amputees, ▲. The change in diameter is given in %. The corresponding effect of histamine (○ and △) is also shown (b).

femoral artery and popliteal artery were measured. In 5 of them the diameters were increased, in 1 decreased and in 2 unchanged. The largest increase was observed at the level of the knee joint (Fig. 46).

Acetylcholine. In 6 legs amputated above the knee the diameter of the superficial femoral artery was measured, and in 7 the deep femoral artery; all showed an increase, the largest being in the deep femoral artery (33 %).

In 5 legs amputated below the knee the diameters were measured in the main artery, and in all cases they were found to have increased at the levels of 10 cm and 20 cm above the knee joint. The diameters were measured at the level of the knee joint in 4 cases, in 2 of which they were increased, in 1 decreased and in 1 unchanged. The mean diameter increase at the knee joint level was approximately 1 % (Fig. 46).

Histamine. The diameters were measured in the stumps of 4 above-knee amputees. In the superficial femoral artery they were increased in 3 cases and decreased in 1, and in the deep femoral artery they were increased in 2 cases, decreased in 1 and unchanged in 1.

The diameter of the main artery was measured in the stumps of 5 below-knee amputees. Only small changes were observed as a rule at the different levels, with a fairly large decrease in only 1 case (22 % at the knee joint level) (Fig. 46).

ATP. In 1 below-knee stump moderate diameter increases were found at all levels.

C. Rate of contrast passage

The rate of contrast passage was higher as a rule when injections of bradykinin, histamine or ATP had been given than at the control investiga-

Site of amputation		No drug	Bradykinin		Acetylcholine		Histamine		ATP	
		cm/sec.	cm/sec.	diff %	cm/sec.	diff %	cm/sec.	diff %	cm/sec.	diff %
Above knee	M	10.0	>10.3	14	11.2	-28	>18	>130	-	-
	range	3.6-19	7.5-13	-37-70	2-30	-70-58	≥10-25	>0-260	-	-
	n	7	6	6	7	7	2	2	-	-
Below knee	M	7.0	>12.6	90	2.7	-37	22	470	30	190
	range	2-13.5	3.5-30	0-260	1.5-4	-60--20	17-30	210-1100	-	-
	n	8	8	8	5	5	5	5	1	1

Table 20. Velocity (V_{max}) of the advancing front of the contrast medium in the superficial femoral artery of above-knee amputees and the popliteal artery of below-knee amputees. The changes are given in per cent (diff.).

Place of injection	Site of amputation	Type of cuff			Dose of bradykinin µg/min. 0 A	0 I	0.5 A	0.5 I
A. femoralis	Above knee	Segmental cuff on both legs	Thigh	M ml/100 ml.min	5.1	3.1	14.5	5.3
				%			216	263
				r ml/100 ml.min	1.6-9.6	1.3-6.4	7.4-18.8	4.4-5.9
				%	-	-	196-240	184-338
				n	6	6	3	3
A. femoralis	Above knee	Bag cuff on the stump. Segmental cuff on the intact leg		M ml/100 ml.min	5.8	3.1	5.7	10.3
				%			17	159
				r ml/100 ml.min	0.5-8.9	1.4-4.0	0.5-10.8	7.3-13.2
				%			0-33	82-263
				n	3	3	2	2
Aorta	Above knee	- " -		M ml/100 ml.min	1.8	1.2	2.3	2.6
				n	1	1	1	1
A. femoralis	Below knee	Segmental cuff on both legs	Thigh	M ml/100 ml.min	2.0	2.3	4.3	6.4
				r ml/100 ml.min	0.6-4.0	1.3-3.7	4.1-8.1	5.2-7.5
				n	8	6	4	2
			Calf	M ml/100 ml/min	1.8	1.2	3.9	2.2
				%			171	61
				r ml/100 ml.min	0.6-3.6	0.8-1.9	2.1-9.9	1.0-4.0
				%			-8-433	-23-167
				n	12	8	8	4

Table 21. Blood flow during intraarterial infusion of bradykinin. M = mean value, r = range of values, n = number of observations. % = the mean percentage individual increase in blood flow induced by bradykinin; the individual values are obtained by com-

tion, but was lower after acetylcholine (Table 20). It was very reduced after noradrenaline.

Bradykinin. The rate of contrast passage was measured in 6 above-knee amputees; in 2 it was found to be higher, in 2 lower and in 2 unchanged. Out of 8 below-knee amputees it was higher in 5 and unchanged in 3.

Acetylcholine. The rate of contrast passage was measured in 7 above-knee amputees. It had increased in 4 cases and decreased in 3. In all 5 below-knee amputees it was found to have decreased.

Histamine. The rate of contrast passage was measured in 2 above-knee and 5 below-knee amputees, and in all cases an increase was found.

ATP. The rate of contrast passage was measured in 1 below-knee amputee, and in this patient it increased greatly.

Dose of bradykinin µg/min.									
1.0		2.0		4.0		6.0		8.0	
A	I	A	I	A	I	A	I	A	I
14.8	6.9	14.7	10.4	13.4	8.9	18.2	9.4	12.9	10.9
277	233	355	316	316	295	315	420	358	170
2.3-26.0	2.6-9.2	6.5-25.8	2.6-21.9	6.0-17.4	1.4-15.1	15.7-19.8	3.4-14.7	-	-
143-370	123-380	198-530	123-670	173-525	108-685	198-505	261-670	-	-
5	5	6	6	5	5	3	3	1	1
7.2	7.6	7.1	10.0	8.0	14.7	-		10.4	19.5
17	250	19	242	22	548	-		19	1290
0.5-13.8	5.4-11.1	0.5-12.9	5.7-16.1	0.5-14.1	8.5-18.5	-	-	-	-
-19-70	203-286	0-70	42-480	0-59	110-1220	-	-	-	-
3	3	3	3	3	3	-		1	1
2.1	0.9	1.6	1.0	-	-	-	-	-	-
1	1	1	1	-	-	-	-	-	-
6.0	5.1	6.0	6.1	8.3	8.0	4.3	4.1	8.1	4.8
3.9-8.1	3.9-6.2	3.1-8.3	3.5-8.8	4.4-12.8	4.2-14.5	1.7-5.6	3.2-5.0	7.9-8.3	4.0-5.5
2	2	7	4	5	3	5	2	2	2
8.1	5.3	7.6	5.8	8.4	5.2	8.4	3.5	7.9	5.8
491	318	445	329	436	284	337	258	242	313
3.2-15.9	1.8-10.7	2.8-20.1	1.4-12.4	3.2-20.4	1.9-9.3	0.7-22.2	2.2-4.8	3.6-13.3	3.4-8.1
113-1020	39-625	-6-225	40-727	588-1760	42-616	-59-1000	180-336	71-373	127-500
6	4	11	6	8	4	7	2	4	4

paring the blood flows before and during bradykinin infusion in the same patient. A = amputated leg and I = intact leg.

D. Effects on the blood flow as measured by plethysmography

Bradykinin. The blood flow was measured during the infusion of bradykinin in 10 above-knee and 12 below-knee stumps (Table 21).

Above-knee amputees. For the blood flow measurements a segmental cuff was used on both legs in 6 patients and a bag cuff on the stump with a segmental cuff on the intact leg in 3 patients (Table 21). The average muscle proportion in the stump was about 63 % for the cuffed segments in the 6 patients, and 31 % for the cuffed stump ends in the 3 patients. The muscle proportion in the intact leg was about 78 % (see chapter IV).

Even small doses of bradykinin in the femoral artery gave rise to high blood flows in the stumps compared with the intact legs in the 6 patients on whom segmental cuffs were used. The same dose rates of bradykinin in the femoral artery of the 3 stumps where bag cuffs were used did not induce

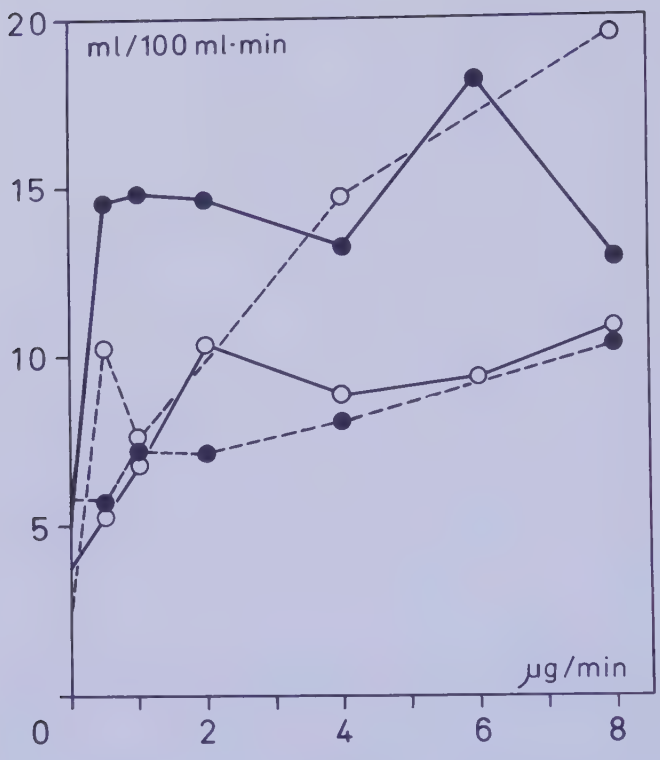


Fig. 48. The effect on the blood flow of infusion of bradykinin into the femoral artery of above-knee amputees. Stumps are marked ● and intact thighs ○. Continuous lines connect cases where segmental cuffs were used and interrupted lines those where a bag cuff was used on the stump and a segmental cuff on the intact leg.

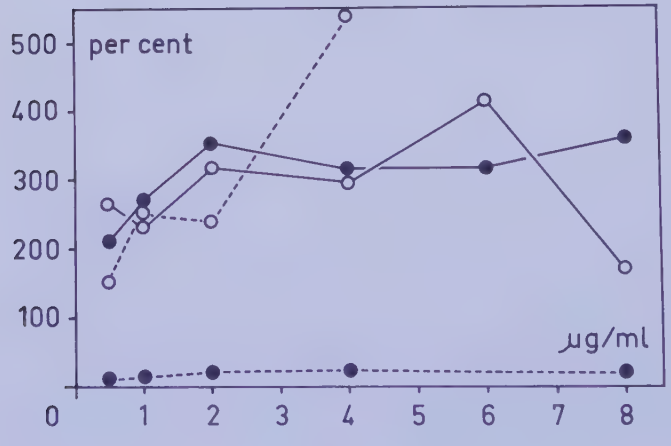


Fig. 49. The change in blood flow in per cent of initial value after infusion of bradykinin into the femoral artery of above-knee amputees. The same symbols are used as in Fig. 48.

such high blood flows (Fig. 48); in one of these three patients, a woman, no effect was noted. The percentage increase compared with the resting blood flow was a little higher in the 6 stump segments than in the intact legs; the difference was larger in absolute terms since the blood flow at rest in the stumps was higher (Fig. 49).

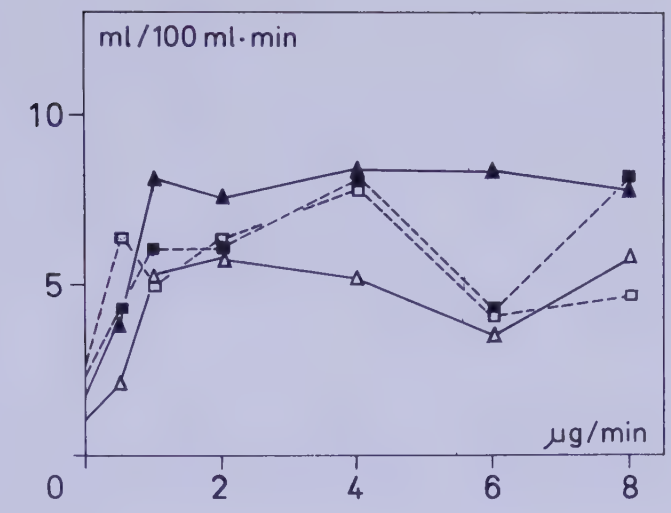


Fig. 50. The figure shows the changes in blood flow after infusion of bradykinin into the femoral artery of below-knee amputees. The stump is marked ▲, intact calf △, thigh of amputated leg ■ and of intact leg □.

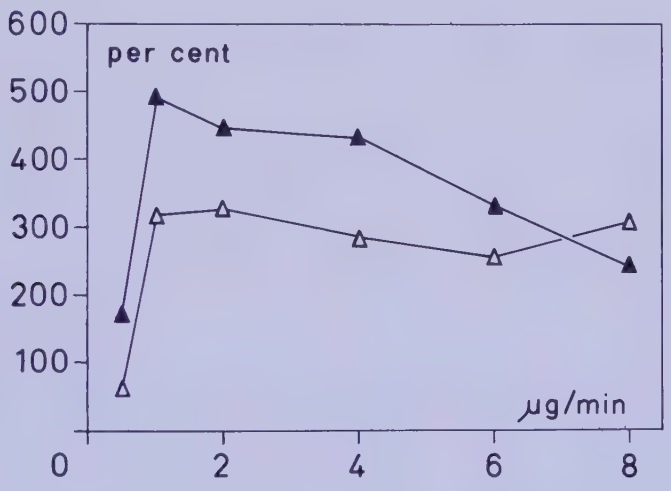


Fig. 51. The changes in blood flow in per cent of initial values after infusion of bradykinin into the femoral artery of below-knee amputees. Stumps are marked ▲ and intact calves △.

The stumps in which the blood flow was measured by a bag cuff showed only a small increase; the corresponding intact legs showed a greater increase (Fig. 49).

In 1 patient intra-aortal infusion of bradykinin had little effect on the blood flow of either side. He was the oldest patient (68 years), and the femoral artery in his stump had been resected.

Below-knee amputees. In all of the 12 below-knee stumps segmental cuffs were used in the blood flow measurements. Even small doses induced as a rule higher absolute flows and a greater percentage increase of the initial value in the stumps compared with the intact legs (Fig. 50 and 51). In 2

Place of injection	Site of amputation	Type of cuff			Dose of acetylcholine mg/min.			
					0		2	
					A	I	A	I
A. femoralis	Above knee	Segmental cuffs on both legs	Thigh	M ml/100 ml.min	3.3	2.2	11.0	9.9
				%			450	890
				r ml/100 ml.min	1.3-9.0	1.0-3.5	-	-
				%			-	-
				n	6	6	1	1
Aorta	"	"	Thigh	M ml/100 ml.min	1.9	1.7		
				%				
				n	1	1		
A. femoralis	"	Bag cuff on the stump. Segmental cuff on the intact leg		M ml/100 ml.min	7.5	2.9		
				%				
				r ml/100 ml.min	6.1-8.9	1.4-4.4		
				%				
				n	2	2		
A. femoralis	Below knee	Segmental cuff on both legs	Thigh	M ml/100 ml.min	1.9	2.3	0.6	1.3
				r ml/100 ml.min	1.3-2.9	1.7-3.2	-	-
				n	3	3	1	1
	"	"	Calf	M ml/100 ml.min	2.2	1.9	0.8	1.1
				%			-30	-7
				r ml/100 ml.min	0.7-4.0	0.7-5.0	0.6-1.0	1.0-1.2
				%			-60-0	-23-9
				n	7	5	2	2
Aorta	"	"	Calf	M ml/100 ml.min	4.1	1.5	-	-
				%				
				n	1	1	-	-

Table 22. Blood flow during intraarterial infusion of acetylcholine. For notations see Table 21.

stumps the flow was unaffected; these patients had undergone re-operation several times, one of them twelve times.

The results suggest that the amputation stumps may be more sensitive to bradykinin than the intact legs. It seems probable that the difference in sensitivity in such a case would be located in the muscular vessels rather than the skin vessels. This may be indicated by the results obtained from blood flow measurements on the thigh stumps with different types of cuffs, i.e. with different muscle proportions in the measuring region. As will be discussed later, the distribution volume of the infused drug must however be considered.

In one above-knee and one below-knee amputee the bradykinin injection

Dose of acetylcholine mg/min.									
5		10		12.5		16		28	
A	I	A	I	A	I	A	I	A	I
6.7	8.4	18.8	10.3	15.5	4.5				
212	345	613	518	72	55	-	-	-	-
4.8-8.8	2.2-21.7	15.6-21.7	7.2-13.4	-	-	-	-	-	-
-20-576	-23-580	450-775	106-930						
4	4	2	2	1	1			-	-
13.8	11.0	-	-	-	-	-	-	-	-
627	545								
1	1								
6.8	21.1	8.3	31.5						
2	434	16	1048						
3.7-9.8	2.2-39.9	7.9-8.7	17.7-45.2						
-58-61	57-811	-11-43	930-1165						
2	2	2	2						
16.5	12.8	8.9	4.8						
-	-	-							
1	1	1	1						
3.8	1.2	10.5	1.4			3.8	-	8.4	-
50	-8	483	100			23	-	135	-
0.5-9.9	0.8-1.6	-	-			2.7-4.9	-	2.8-14.0	-
-29-280	-16-2	-	-			22-23	-	20-250	-
5	2	1	1			2	-	2	-
4.9	1.0	-	-			-	-	-	-
22	-33	-	-			-	-	-	-
1	1	-	-			-	-	-	-

was repeated after intra-arterial atropine had been given, and the blood flow showed in the main the same values for the different doses of bradykinin with as without atropine.

Acetylcholine. The blood flow was measured during the infusion of acetylcholine in 9 above-knee and 7 below-knee amputees.

In 7 *above-knee amputees* a segmental cuff was used in measuring the blood flows, which were found to increase with increasing doses of the drug in both the stump and intact thigh (Table 22). In 2 patients in whom the blood flow was measured with a bag cuff in the stumps, there was no noteworthy increase in the stumps but an increase was observed, on the other hand, in the intact leg. In these two patients the stump showed a muscle

Place of injection	Site of amputation	Type of cuff			Dose of histamine µg/min. 0 A	0 I	5 A	5 I	7 A	7 I	8.8 A	8.8 I	10 A	10 I
A. Femoralis	Above knee	Segmental cuffs on both legs	Thigh	M ml/100 ml.min	3.5	2.1	10.9	5.8	7.5	27.1	-	-	11.4	9.0
				%			372	282	-17	720			350	440
				r ml/100 ml. min	2.0-9.0	1.0-3.3	9.9-11.8	4.8-6.8			-	-	8.3-14.2	4.7-13.1
				%			253-490	183-380					197-485	280-670
				n	4	4	2	2	1	1	-	-	3	3
		Bag cuff on the stump. Segmental cuff on the intact leg	Thigh	M ml/100 ml.min	5.7	3.3	18.0	6.0	-	-	-	-	12.9	7.8
				%			216	32					126	136
				n	1	1	1	1	-	-	-	-	1	1
A. Femoralis	Below knee	Segmental cuff on both legs	Thigh	M ml/100 ml.min	2.7	3.2*					12.8	8.3	6.6	6.0
				r ml/100 ml.min	2.5-2.9	2.8-3.5					-	-	-	-
				n	2	2					1	1	1	1
			Calf	M ml/100 ml.min	1.7	1.0	13.4	-			11.0	4.6	15.0	3.2
				%			592	-			400	475	745	14
				r ml/100 ml.min	0.5-2.5	0.8-2.8	5.0-20.4	-			-	-	4.2-21.2	-
				%			520-715						740-750	-
				n	5	2	3	-			1	1	4	1

Table 23. The effects of histamine on the blood flow. For notations see Table 21.

proportion of 37 % and 41 %, while the muscle of the intact leg comprised 67 % and 75 %. The above-knee stumps that were investigated with a segmental cuff showed the same values as those investigated in the same way during bradykinin injections, and the former had a higher proportion of muscle (63 %).

Segmental cuffs were used on all below-knee amputees. The blood flows in the stump and intact calf decreased as a rule with small doses of the drug, but with the doses 5 and 10 mg/min the stump flow increased to a greater extent than that of the intact leg. The blood flow in the thigh was recorded in only a few below-knee amputees, and these flows were relatively similar, possibly with a tendency to a higher flow in the amputated leg.

One below-knee amputee was given acetylcholine intra-aortally, and showed small changes in blood flow. One patient with bilateral below-knee amputations, who was given acetylcholine bilaterally in the femoral artery, reacted with an increase in the blood flow in one of the stumps, from 4.0 to 14 ml/100 ml · min, and with a decrease in the flow in the other stump from 3.5 to 2.8 ml/100 ml · min.

Place of injection	Site of amputation	Type of cuff			Dose of ATP mg/min			
					0		2.8	
					A	I	A	I
A. Femoralis	Below knee	Segmental cuff on both legs	thigh	M ml/100 ml/min	3.0	3.1	20.1	20.0
				n	1	1	1	1
			calf	M ml/100 ml/min	3.0	1.2	16.3	9.2
				n	1	1	1	1

Table 24. The effects of ATP on the blood flow in one below-knee amputee. For notations see Table 21.

Place of injection	Site of amputation	Type of cuff			Dose of noradrenaline µg/min					
					0		2.5		5.0	
					A	I	A	I	A	I
A. Femoralis	Above knee	Bag cuff on the stump	Thigh	M ml/100 ml.min	8.9	3.4	1.1	0.7	2.8	4.8
				range ml/100 ml.min	8.9-8.9	1.4-5.3	-	-	-	-
		Segmental cuff on the intact leg		n	2	2	1	1	1	1
A. Femoralis	Below knee	Segmental cuff on both legs	Calf	M ml/100 ml.min	1.1	1.3	0.6	0.9		
				n	1	1	1	1		
Aorta	-"-	-"-	-"-	M ml/100 ml.min	4.1	1.5	1.4	0		
				n	1	1	1	1		

Table 25. The effects of noradrenaline on the blood flow. For notations see Table 21.

Histamine. In 4 above-knee amputees, in whom the blood flow was measured with a segmental cuff, histamine had a somewhat irregular effect on the blood flow in the stump compared with that in the intact leg, but the number of investigations was so small that no definite conclusion can be made. In the only case where a bag cuff was used in the blood flow measurements the flow in the stump was considerably larger than in the intact thigh with a dose rate of 5 µg/min, while 10 µg/min gave relatively similar flows. The muscle proportions in the stump and intact thigh were 37 % and 75 % respectively (Table 23).

In 4 below-knee amputees (1 bilateral) the blood flow in the stumps increased greatly. In only 2 patients was the intact leg investigated; in one calf the blood flow increased greatly, and in the other only slightly (Table 23).

ATP. ATP was tested in one below-knee amputee, and gave rise to a large

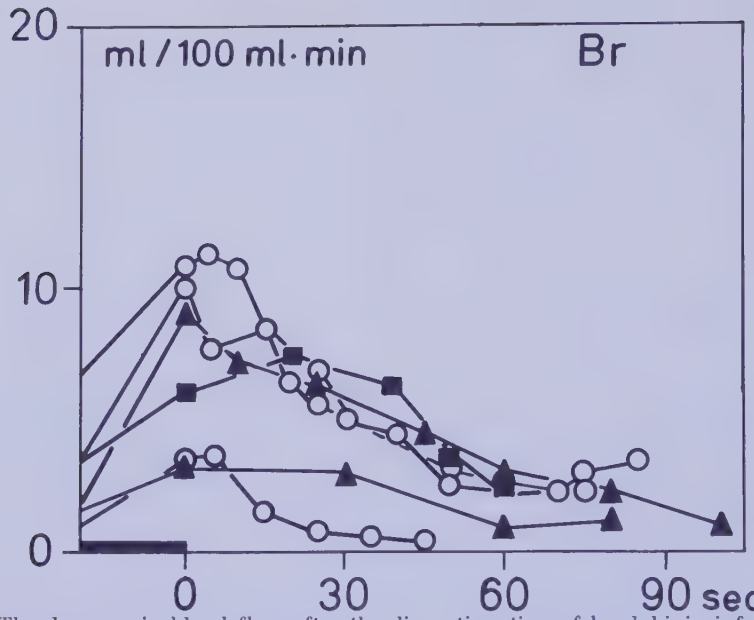


Fig. 52. The decrease in blood flow after the discontinuation of bradykinin infusion in the intact thigh of 3 above-knee amputees (○), in 2 below-knee stumps (▲) and in the thigh of 1 below-knee amputated leg (■). The thick continuous line along the abscissa represents an infusion time of 10 minutes. The dose rate was 6 μg/min.

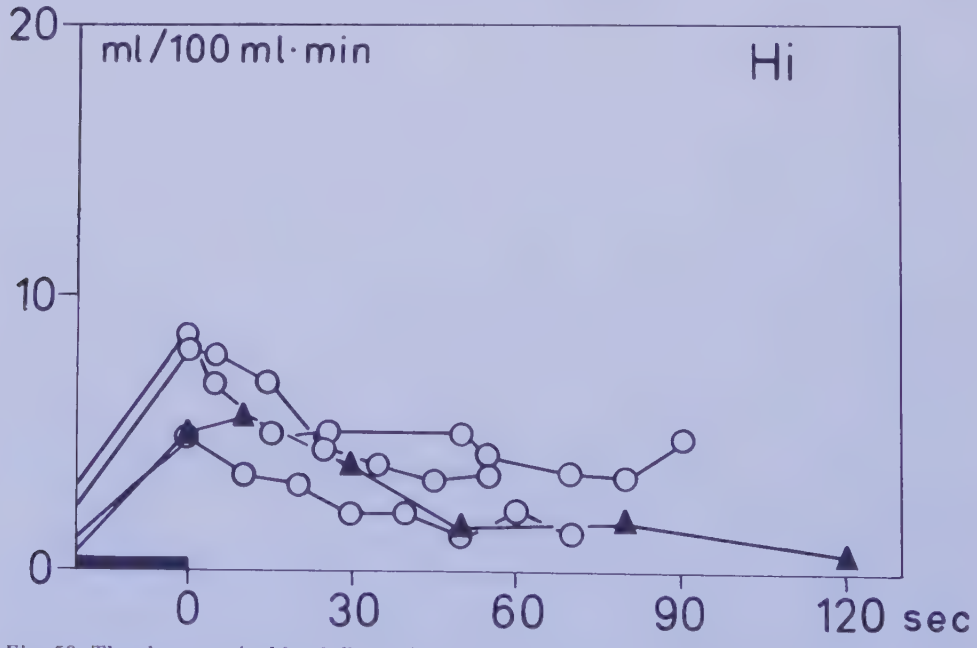


Fig. 53. The decrease in blood flow after discontinuation of histamine infusion. Dose rate 7–10 μg/min. For notations see Fig. 52.

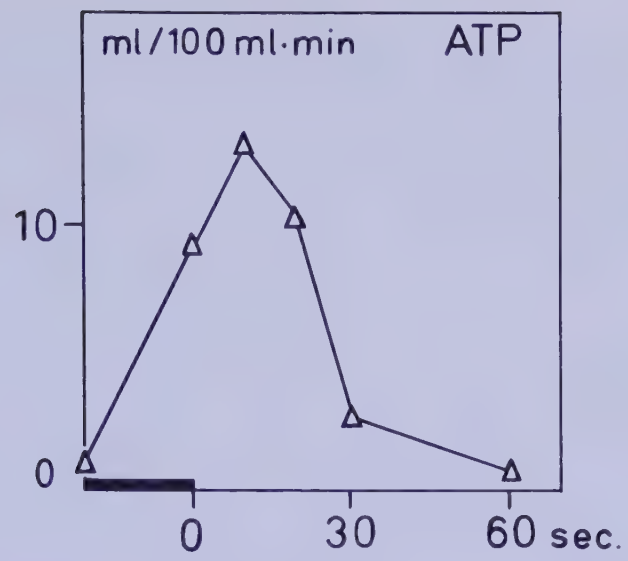


Fig. 54. The decrease in blood flow after discontinuation of ATP infusion in the intact calf of a below-knee amputee. Dose rate 2.8 mg/min.

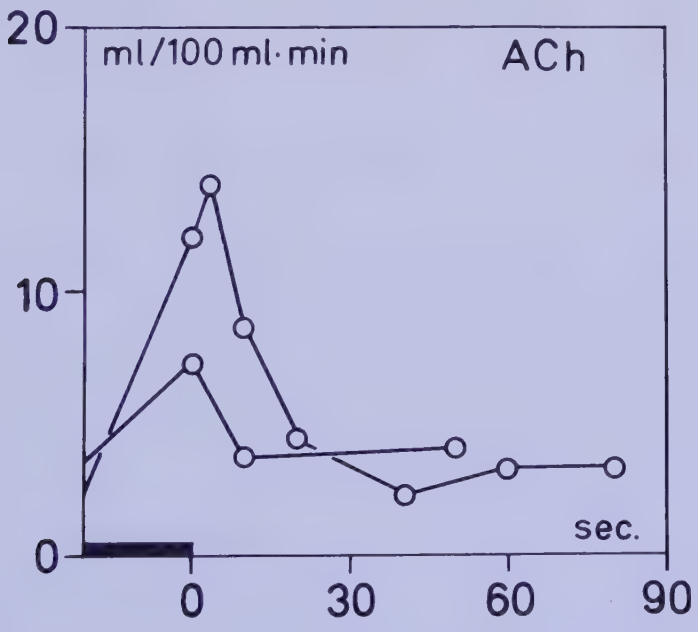


Fig. 55. Decrease in blood flow of intact thigh in 2 above-knee amputees (○) after discontinuation of acetylcholine infusion. Dose rate 10 mg/min.

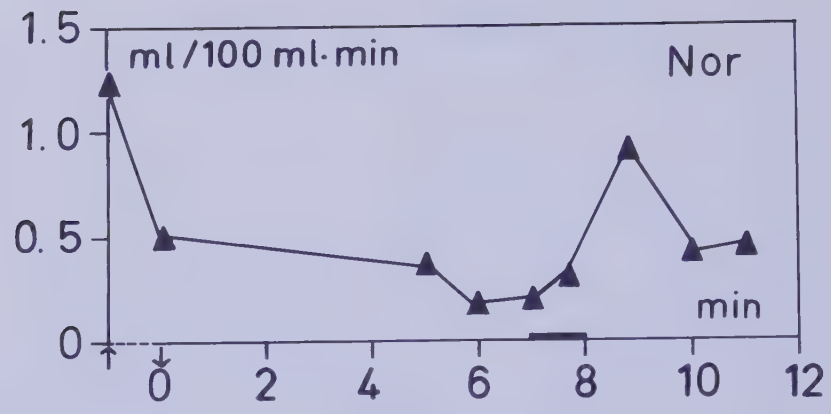


Fig. 56. The effect of 2.5 μg/min of noradrenaline, injected for a period of 5 minutes (between the arrows), on the blood flow of a below-knee stump. The blood flow was decreased and a dose of 10 μg bradykinin given for 1 minute (thick continuous line along the abscissa) gave little effect.

bilateral increase in the blood flow of the thigh: the blood flow in the stump increased to a greater extent than that in the intact calf (Table 24).

Noradrenaline. Noradrenaline was given to 2 above-knee and 2 below-knee amputees. This drug produced a marked reduction in the blood flow compared with the resting state in all patients even when the initial resting blood flow was high (Table 25).

Residual effects on the blood flow after the discontinuation of vasoactive drugs

The blood flow was measured in a number of patients after the administration of drugs was discontinued. These measurements showed that the effect of all the drugs was transient, except for noradrenaline.

When the bradykinin injection was discontinued the blood flow in all patients returned to the resting value within 60 seconds. A relatively marked decrease in blood flow had occurred as early as after 20 seconds (Fig. 52).

Histamine and ATP induced similar effects (Fig. 53 and 54). In the 2 patients in whom the effects of acetylcholine were studied the decrease was even more rapid (Fig. 55).

In the below-knee amputee in whom the blood flow was measured after the discontinuation of a noradrenaline injection a low blood flow was still recorded after 8 minutes, and a simultaneous dose of 10 μg bradykinin given for 1 minute produced an insignificant increase in the blood flow. This did not rise to the original resting value (Fig. 56).

E. Side effects and complications

a. *General effects*

Bradykinin. All patients exhibited blotchy redness of the skin from the level of the navel to the stump or foot. At the same time the patient experienced a feeling of warmth which was often pleasant and never uncomfortable. The blood pressures, measured by palpation, were normal and unchanged. One patient had vague feelings of discomfort after only 0.5 μg/min, but there were no general symptoms.

One patient had a feeling of swelling in the stump.

Acetylcholine. All patients had pain around the site of puncture in the inguinal region after the infusion started. In most of them the pain soon disappeared and they even tolerated a higher dose, but in some patients the pain persisted. The blood pressures were not affected.

One patient vomited and another had a vague feeling of discomfort (this patient had the same feeling during the bradykinin infusion).

Histamine. All patients had a feeling of warmth and exhibited skin redness below the level of the navel. One patient had a slight headache and mild tachycardia. The blood pressures were unaffected.

ATP. The patient felt warm, but no other symptoms were noted.

Noradrenaline. One patient complained of nausea. No other symptoms were noted.

b. *Pain*

Some patients experienced pain during the bradykinin and acetylcholine infusions. The other drugs did not induce pain.

Bradykinin. In 1 male below-knee amputee with phantom pains these symptoms were accentuated when the dose given was 0.5 μg/min. The pains increased further when the dose was raised to 2 μg/min but remained unchanged when a dose of 8 μg/min was given. The corresponding arteriography is showed in Fig. 45 b. These pains disappeared when the infusion was discontinued for arteriography. Neither urografin, acetylcholine nor histamine provoked pain even when the blood flows in the stump increased. Arteriography revealed an abundance of tortuous arteries. In 1 female below-knee amputee who often suffered from phantom pains these symptoms occurred at the dose 2 μg/min, increased at 6 μg/min and disappeared within 30–40 seconds after the infusion had been discontinued. The pains returned and were more intensive, when the infusion of bradykinin was recommenced. Arteriography was performed immediately at the end of the second infusion, and the pains persisted for about 10–15 seconds after the arteriography was

completed. Histamine gave rise to the same blood flow increase but provoked no pain. Arteriography showed an abundance of tortuous arteries.

One above-knee amputee who suffered from severe phantom pains was given a bradykinin infusion first before and then after an intra-aortal injection of 1 mg atropine, and this patient complained of such pains only in connection with the latter infusion, when a dose of 4 μg/min was given. They disappeared when the infusion was discontinued. The same blood flows were recorded at the dose 4 μg/min before and after the atropine injection. Arteriography revealed a moderate number of arteries, several of which were tortuous.

In 1 below-knee amputee with pronounced stump pains, twitching of the type which has been called stump epilepsy occurred on the infusion of bradykinin. The blood flow could not be measured, but arteriography was performed and showed an abundance of arteries in the stump, many of which were tortuous.

In 1 above-knee amputee with severe phantom pains, who before the infusion of bradykinin had stump epilepsy, this disappeared while the infusion was in progress and returned when it was discontinued.

Acetylcholine. In one above-knee amputee with frequent phantom pains these symptoms increased during the infusion of 2.8 mg/min. The blood flow in the stump rose then from about 3 to 7 ml/100 ml · min. In the intact leg it was constant at about 26 ml/100 ml · min. When the dose was decreased to 1.6 mg/min the pain disappeared and did not return when the dose was again increased to 2.8 mg/min. At these two doses the blood flow in the stump was about 3 ml/100 ml · min. Arteriography showed the presence of tortuous arteries.

Discussion

The arteriographic effects of bradykinin, acetylcholine, histamine and ATP, which on intra-arterial injection are transiently active, should be considered in relation to the blood flow values obtained after the discontinuation of these drugs. Even when the change-over was made as rapidly as possible it must be assumed that the blood flow would have decreased to a certain extent between the discontinuation of the drug and the time at which the arteriographic phase was utilized for evaluation. Thus the drug concentration affecting the vascular walls was probably lower in this latter time interval than during the injection of the drug before arteriography. Nevertheless some changes in diameters and rate of contrast passage were apparent.

The concentration of the drugs injected was probably higher in the blood of the amputated side. This may be explained by the fact that the tissue volume of the stump side was smaller and that the absolute quantities of the drug passing per unit time were similar on both sides. The exact volume of tissue reached by the drug cannot be assessed precisely. Reddening of the skin from the level of the navel to the foot or stump end was observed when, for example, bradykinin was injected, and this indicated that the substance was distributed not only in the leg but also in both the abdominal wall and gluteal regions. An approximate evaluation of the tissue volume reached by the drug is therefore unreliable. The volume of drug distribution was assessed schematically as approximately 0.6–0.7 for the thigh stump side and 0.8 for the calf stump side compared with 1.0 for the intact side. Another problem in evaluating the results is the uncertainty as to how the drug is distributed in the tissue via the vascular network, i.e. whether uniformly, or unevenly, those regions which have the largest blood flow at the commencement of the injection receiving more of the drug. In this latter case further vasodilatation may perhaps be produced in already dilated sections, and other regions are only gradually dilated (this possibly becoming progressively more rapid as the blood flow and thus the amount of drug increases).

Similarly the sensitivity in different vascular sections and tissue regions may vary. It is therefore uncertain whether there is a true hypersensitivity to vasodilator drugs in the stump musculature.

The arteriographic investigation gives no information on whether the substance acts specifically or mainly on any special vascular section between the smallest visible arteries and veins. Whether the blood flow increase is caused by the dilatation of arterioles, pre-capillary sphincters or post-capillary venules cannot be resolved in an arteriography. The dilatation recorded in the large arteries after the injection of a vasoactive drug may be due to direct or possibly reflex influence on the arterial wall.

Acetylcholine increased the flow in above-knee stumps but the absence of contrast-filled arteries in the region supplied by the superficial femoral artery may indicate that the deep femoral arterial region is more sensitive to this drug. The latter vascular region could thus contribute to the plethysmographically recorded blood flow increase which is simultaneous with distinct contrast-filling in the region. The superficial femoral artery is ligated at the amputation and any branches that remain or any new branches that arise in the stump may be functionally different. The deep femoral artery and its branches still supply the thigh muscles, and apart from some atrophic regions still retain this function. This may be one possible explanation for the varying degrees of sensitivity to acetylcholine in different stump regions.

Type of amputation		No drug		Bradykinin				
		BF_R	BF_P		BF_R		BF_P	
		ml/min.	ml/100 ml.min	Dose µg/min.	ml/min.	Diff %	ml/100 ml.min	Diff %
Above knee	M	63	5.9	5.1	68	38	145	216
	range	19-136	1.6-9.6	2.5-8	36-98	50-103	60-21.8	17-420
	n	6	6	6	6	6	6	6
Below	M	35	2.2	6.2	99	164	9.1	394
	range	11-64	0.8-3.6	4-8	17-354	10-450	3.1-22.2	62-1220
	n	8	8	8	8	8	8	8

Table 26. The blood flow measured by venous occlusion plethysmography is called BF_P, and that obtained from the arteriographies BF_R. The difference means the quotient of the blood flow during the injection of the drug and at rest.

The observed dilatation of the superficial femoral artery may be due to an effect on the muscle of the arterial wall.

It is also possible that the reaction of the deep femoral arterial region to acetylcholine may cause this to shunt contrast-filled blood and thereby reduce the flow in the superficial femoral artery especially if a sluggish flow in this artery facilitates the enzymatic breakdown of the short-lived acetylcholine to a significant extent. This would apply both to legs amputated above the knee and below.

The blood flow values obtained by plethysmography and those assessed by the movement of the contrast medium in large arteries cannot be compared directly.

The blood flow which passes through a certain level of a main artery is distributed in the tissue distal to this level, but the exact tissue volume cannot be calculated. A plethysmographic value refers primarily to the segment enclosed by the measuring cuff, and because of different tissue proportions, this cannot always be generalized as being representative for the entire extremity.

For these reasons only limited comparison is possible between the changes in blood flow as measured by the two methods. Such changes can easily be induced by drugs. Thus for a change in the blood flow as measured by plethysmography there should be some corresponding change in the volume of the contrast column which passes through a level proximal to the plethysmographic measuring cuff.

In a thigh stump a comparison is very unreliable because, due to the anatomical conditions, the region of the deep femoral artery does not permit evaluation of the rate of contrast passage. A comparison only between the estimated volume passing through the superficial femoral artery 8 cm below the greater trochanter and the flow recorded at venous occlusion plethysmo-

Acetylcholine					Histamine					ATP				
	BF_R		BF_P			BF_R		BF_P			BF_R		BF_P	
Dose mg/min	ml/min	Diff %	ml/100 ml.min	Diff %	Dose µg/ min.	ml/ min	Diff %	ml/100 ml.min	Diff %	Dose mg/min	ml/ min	Diff %	ml/ 100 ml. min	Diff %
7.6	79	-3	9.3	140	8.5	99	92	19.4	230					
2.8-12.5	15-183	-42-144	4.8-15.9	-11-455	7-10	92-105	28-156	11.7-27.1	183-178					
4	4	4	4	4	4	2	2	2	2					
19	22	-44	6.9	193	10	136	256	14.0	696	2.8	250	290	16.3	482
8-28	9-30	-75-0	0.5-14	-86-460	8-10	81-173	136-395	4.2-21.2	100-1640	-			-	
4	4	4	4	4	4	4	4	4	4	1	1	1	1	1

graphy may therefore be misleading, particularly if it is uncertain whether the deep and superficial regions of the femoral artery react similarly to drugs. Comparison between the two methods has been attempted, however (Table 26). Neither for bradykinin nor histamine was there any distinct correlation. Nevertheless a blood flow increase with the one method did correspond to an increase with the other. Acetylcholine decreased the volume of contrast-mixed blood in the superficial femoral artery in 3 patients and increased it in 1 case. In 1 patient on whom a bag cuff was used a decrease in the blood flow was recorded plethysmographically, and in the other 3 there was an increase which was independent of the dose given. Similar results were obtained from comparison between the blood flow methods for the below-knee stumps, where with both methods bradykinin and histamine showed a tendency in the majority of patients to induce a blood flow increase. With acetylcholine the roentgenologically recorded "flow" decreased in all 4 patients on whom both methods were used, while the plethysmographic values increased in 3 and decreased in one. The roentgenological and plethysmographic flow determinations were not made at the same time. The former should in fact be compared with the plethysmographic flows at lower doses of the drugs, since the concentration change immediately after cessation of drug infusion cannot be evaluated with certainty.

A comparative study of the results from arteriography and plethysmography may with certain reservations support the view that the stump tissue reacted by greater vasodilatation to bradykinin than that of the intact leg, and that this applied especially to the region supplied by the superficial femoral artery. The reverse may possibly hold for acetylcholine. Histamine, which was given to a small number of patients, produced no definite special mode of reaction in the amputated leg compared with the intact leg, but there appeared to be a tendency for a stronger effect in the skin than the muscular regions.

The reaction in the form of phantom pains which occurred during the bradykinin infusion in some amputation stumps appeared to be definitely correlated to this drug. It was reproducible during the investigation and it is therefore improbable that this reaction was spontaneous. One above-knee amputee complained of phantom pains during an acetylcholine infusion. This patient often suffered from attacks of such pains and it is possible that it was a similar attack that coincidentally occurred during the infusion. It was of interest that the blood flow increased during the attack. Observations with regard to pain and stump epilepsy allow no conclusions as to their origin. They are of interest, however, in that they indicate that physiologically occurring substances or metabolites may play a part in the pain mechanism, possibly by the vasodilatation they provoke.

Summary

1. The arteriographic picture of both the above-knee and the below-knee stumps showed increased contrast-filling of the peripheral vessels after close arterial infusion of bradykinin, histamine and ATP. In the majority of stumps acetylcholine produced a decrease in the contrast filling of the distal branches of the superficial femoral and popliteal arteries in the above- and the below-knee amputees, respectively. Injection of noradrenaline produced a general decrease in the contrast filling of the peripheral arteries.

2. The arterial diameters increased after bradykinin, acetylcholine and ATP, remained unchanged after histamine and decreased after noradrenaline. There was on an average an increase in the rate of passage of the contrast medium after bradykinin, histamine and ATP. As a rule there was a decrease after acetylcholine; similar but more prolonged decrease occurred after noradrenaline.

3. After bradykinin the blood flow, as measured by venous occlusion plethysmography, showed even with small doses a greater increase in the stump than in the intact leg. With acetylcholine the blood flow increased in a number of stumps but decreased in others. Histamine increased the blood flow in all stumps except one. ATP, in the only patient in whom it was tested, provoked a large increase in blood flow. Noradrenaline was tested in four cases and in all reduced the blood flow considerably. The effects of bradykinin, acetylcholine, histamine and ATP on the blood flow were only transitory, while noradrenaline had a more prolonged after-effect.

4. The vessels of the muscles of the amputation stump may possibly be more sensitive to bradykinin than those of the intact leg. The effective dose rate per tissue volume is, however, difficult to determine for the stump side as compared to the intact side.

CHAPTER VI

Clinical status in relation to the blood flow and vascular anatomy in the amputation stump

Introduction

An amputee often suffers from ulcers and skin tenderness in the stump. This also swells at times so that the volume changes, and the socket of the prosthesis may fit differently at different times of the day. Pain in the amputation stump and phantom pains also occur frequently.

In discussing the roentgenological and physiological findings in the previous chapter, no consideration was taken of the clinical status of the patient or case history records of different types of symptoms. In the following section pain in the amputated leg will be discussed in relation to the blood flow and vascular anatomy in the stump.

According to Leriche (1949), some patients with symptoms in the amputated leg, such as tenderness and pain in the stump, and also phantom pains, have hypocirculation in the stump and others hypercirculation. His material consisted of 3 patients. Erikson & Hulth (1961) found a tendency to increased vascularization in stumps in which pain occurred, in a series of 33 above- and below-knee amputees. Gillis (1964) also considered that pain may be related to the local circulation. His investigation, however, comprised only the venous system as far as this could be studied by intraosseous phlebography.

It therefore seemed justifiable to study the present large series from these limited aspects.

The clinical investigation was carried out in collaboration with Assistant Professor Anders Hulth, M. D., Department of Orthopedic Surgery, University Hospital, Göteborg. The full results of this investigation will be reported elsewhere.

Method

A. *Evaluation of symptoms in the amputated leg.* The degree of phantom and stump pains was assessed with the aid of case note records complemented by interviews with the patients themselves. The classification of the symp-

toms into phantom pains and stump pains has been made by previous investigators, who have considered that both the aetiology of the pains and their treatment may vary (Gillis, 1964). There appears to be no convincing evidence, however, in favour of different aetiologies of stump pains, and also, in many cases these pains are difficult to differentiate. Phantom pains may sometimes be related to the amputation stump. It was therefore chosen to make a survey of the degree of pain experienced in the amputated leg by different patients, and these findings were analysed with respect to 1) duration, 2) frequency and 3) intensity. Each of these factors was evaluated on a 3-graded scale. The maximal degree of pain with respect to duration, frequency and intensity was thus represented by 9 points. The material was then re-classified into groups according to these points: Group 1, no or insignificant pain in the amputated leg (1–3); group 2, moderate pain in the amputated leg (4–6); group 3, severe pain in the amputated leg (7–9).

The following three case history summaries represent the three groups of patients:

1. A 12-year old boy who at the age of 6 years underwent right below-knee amputation after a traffic accident. A post-operative infection occurred, and the wound was re-examined at a further operation. Since then the patient has never had pain or any other symptoms in the stump. On isolated occasions he has had slight irritation of the toes of the phantom limb. He skates, skis, plays football and cycles. He is thus assigned to the group with no or insignificant pain in the amputated leg. Case no. 9753/61, Fig. 14.

2. A 45-year old man who underwent right above-knee amputation after a train accident at the age of 35 years. He changed his occupation from building work to turning after re-training. He manages his work well but has to be absent for 4–5 days each month because of friction sores on the stump. He is unable to walk for long periods at a time because of pain in the stump, which also swells. Four or five times a year he has nightly phantom pains in the toes,which prevent him from sleeping. He keeps in good general condition by regular gymnastics and swimming with a group of handicapped persons. This patient has been assigned to the group with moderate symptoms of pain. Case no. 16786/61.

3. A 27-year old man who underwent right above-knee amputation at the age of 23 years, after a traffic accident. The accident occurred one year before the amputation, but infection occurred and the leg could not be saved. The patient has changed his occupation from welder to factory inspector. He suffers from constant phantom pains which increase with the years, and also tenderness and pain in the stump. He has the feeling that his foot is being squeezed as in a vice (this part of the body was not injured). The pains increase towards evening and are associated with cold sweats when

the amputation stump also sweats and the prosthesis socket becomes wet inside. The patient is often awakened during the night by the pains and has become restless and nervous and has to take many analgesics. He is able to walk 300–400 metres without help but has an invalid car. His pains prevent him from working 1–2 days each week. Case no. 10277/61, Fig. 12.

Results

I. Comparison between arteriographical, plethysmographical and clinical findings

The blood flow was measured by plethysmography in 20 unilateral above-knee amputees and 25 unilateral and 3 bilateral below-knee amputees (for method, see chapter IV), and the greater number of these patients also underwent femoral arteriography (for method, see chapter II). The results are shown in Table 27 and 28.

Above-knee amputees. 10 of the patients had no or only very slight pain in their amputation stumps. Only one of these patients had undergone further operation since the amputation, this consisting of skin transplantation to the stump. Clinical examination revealed no ulcers or tendency to ulcers in these 10 patients. Among the group of 4 patients with moderate symptoms one had undergone re-operation three times in the amputation stump. This patient and also 2 other patients in this group had friction sores on the amputation stumps. Six patients had severe pains in their amputation stumps. Three of these patients had undergone re-operation on the stump, two of them three times. Three patients had ulcers, tendency to ulcers and/or redness on the amputation stump. The mean age in the three groups was about 40 years.

In the patients with no pain the mean value of *blood flow at rest* was approximately the same in the stump as in the intact leg. i.e. 2.5 and 2.4 ml/100 ml · min, respectively. In the patient with moderate pain these mean values were 2.2 and 1.9 ml/100 ml · min, respectively. The patients with severe pain in the stump or phantom limb had a mean blood flow at rest of 3.7 ml/100 ml · min in the stump and 2.9 ml/100 ml · min in the intact leg.

The *maximum blood flow* was measured during reactive hyperemia in 5 patients who had no or insignificant pain in the amputation stump. The mean value for the maximum flow in the stump was 8 ml/100 ml · min and in the intact leg 16 ml/100 ml · min. In three patients with moderate pain in the stump or phantom limb this mean value was 13 in the stump and 21 in the intact leg. In 5 patients with severe pain in the stump or phantom

		No pain in stump or phantom limb				
		No. of cases	Age at examination (years)	Time since amputation (years)	Amputated leg	Intact leg
Blood flow at rest, ml/100 ml · min		10	40 (21-59)	3 (1-7)	2.5 (0.8-3.6)	2.4 (1.0-4.1)
Maximum bloodflow during reactive hyperemia ml/100 ml.min.		5	38 (24-57)	3 (1-6)	8 (2-21)	16 (6-25)
Presence of spiralled arteries in stump	None	8	40 (21-59)	3 (1-7)		
	Moderate	2	41 (37-45)	4 (3-6)		
	Abundant					
Richness of arteries in stump	Few	7	39 (21-59)	2 (1-6)		
	Moderate	3	42 (37-45)	5 (3-7)		
	Abundant					
Presence of spurs	Present	5	46 (24-59)	4 (1-7)		
	Not present	5	34 (21-57)	2 (1-7)		
Wall change in main artery	None	7	34 (21-57)	2 (1-6)		
	Moderate	3	53 (45-59)	5 (4-7)		
	Obliteration					
Presence of A-V anastomoses	Present					
	Not present	10	40 (21-59)	3 (1-7)		

Table 27. The table shows the relationship between the arteriographic and plethysmo-

limb the mean value was 18 ml/100 ml · min in the stump and 21 ml/100 ml · min in the intact leg.

On comparing the degree of pain with the *incidence of spiralled arteries* in the amputation stump a tendency to an increase in the number of such arteries was seen in the stump with increasing degrees of pain.

The *vascular richness* was seen to increase in the amputation stump with greater degree of pain.

Spurs were observed in 5 patients without pain in the amputated leg, in 3 patients with moderate pain and in 4 with pronounced pain. The mean age in these groups varied between 46 and 49 years. In 5 patients with no or only slight pain, and in 2 patients with pronounced symptoms, no spur

Moderate pain in stump or phantom limb					Severe pain in stump or phantom limb				
No. of cases	Age at examination (years)	Time since amputation (years)	Amputated leg	Intact leg	No. of cases	Age at examination (years)	Time since amputation (years)	Amputated leg	Intact leg
4	46 (37-56)	14 (10-22)	2.2 (1.2-5.0)	1.9 (1.2-2.6)	6	42 (21-68)	13 (1-49)	3.7 (1.1-9.3)	2.9 (1.2-5.2)
3	46 (37-56)	14 (12-22)	13 (11-18)	21 (7-37)	5	40 (21-68)	13 (1-49)	18 (5-39)	21 (1-50)
1	48	12							
2	42 (37-45)	11 (10-12)			5	40 (21-68)	13 (1-49)		
					1	55	6		
1	48	12			1	68	49		
2	42 (37-45)	11 (10-12)			4	43 (21-46)	6 (1-10)		
					1	55	6		
3	46 (37-56)	14 (10-22)			4	49 (21-68)	18 (7-49)		
					2	29 (21-37)	3 (1-5)		
3	46 (37-56)	14 (10-22)			4	31 (21-46)	6 (1-10)		
					2	62 (55-68)	28 (6-49)		
1	45	10							
2	43 (37-48)	12 (12-12)			6	42 (21-68)	13 (1-49)		

graphic findings in the three groups of above-knee amputees.

was observed. The mean ages in these groups were 34 years and 29 years respectively.

In the three groups of patients, i. e. with no or slight pain, with moderate pain and with pronounced pain, no *arterial changes* were observed in 7, 3 and 4 patients respectively. The mean age in these groups varied between 31 and 46 years. In 3 patients with slight pain arteriosclerosis-like changes were observed. The mean age of these patients was 53 years. In 2 patients with pronounced pain in the amputation stump the superficial femoral artery was completely obliterated. The mean age of these patients was 62 years.

In only one above-knee amputee, a 45-year old man, were *arteriovenous*

		No pain in stump or phantom limb				
		No. of cases	Age at examination (years)	Time since amputation (years)	Amputated leg	Intact leg
Blood flow at rest, ml/100 ml. min.		11	35 (12-62)	9 (1-29)	1.9 (0.8-2.9)	3.3 (1.7-5.4)
Maximum blood flow during reactive hyperemia ml/100 ml.min.		7	36 (15-62)	9 (1-29)	9 (2-18)	22 (8-51)
Presence of spiralled arteries in stump	No	5	39 (12-58)	8 (1-17)		
	Moderate	2	23 (18-27)	2 (1-2)		
	Abundant	0	-	-		
Richness of arteries in stump	Few	5	39 (12-58)	8 (1-17)		
	Moderate	2	23 (18-27)	2 (1-2)		
	Abundant	-	-	-		
Presence of spurs	Present	2	25 (12-38)	4 (1-6)		
	Not present	5	48 (18-58)	7 (1-17)		
Wall change in main artery	No	5	29 (12-47)			
	Moderate	1	58	17		
	Obliteration	1	38	1		
Presence of A-V anastomoses	Present	3	19 (12-27)	3 (1-6)		
	Not present	4	46 (38-58)	8 (1-7)		

Table 28. The table shows the relationship between the arteriographic and plethysmo-

anastomoses observed in the amputation stump. This patient had moderate pain in the stump. The other patients whose mean age varied between 40 and 43 years showed no arteriovenous anastomoses.

Below-knee amputees. Plethysmography of the stump and intact calf was performed on 25 unilateral below-knee amputees. Eleven of these patients had no or only very slight pain in the amputated leg. Three of these had undergone reamputation because of exostoses. One patient had pronounced friction sores. Two of the patients had ulcers on the stump and one patient had skin redness on the stump.

Eight patients had moderate pain. Of these, 4 had been reamputated because of exostoses, 2 had tenderness in the stump, 1 had troublesome adhesions and 1 had pronounced swelling in the stump.

Six patients had severe pain in the amputated leg. Five of these had been re-

Moderate pain in stump or phantom limb					Severe pain in stump or phantom limb				
No. of cases	Age at examination (years)	Time since amputation (years)	Amputated leg	Intact leg	No. of cases	Age at examination (years)	Time since amputation (years)	Amputated leg	Intact leg
8	45 (27-65)	5 (1-11)	2.3 (0.8-5.0)	1.8 (0.7-3.0)	6	47 (26-61)	5 (2-11)	2.5 (1.1-4.0)	2.0 (0.9-4.1)
6	45 (37-65)	6 (2-11)	10 (2-21)	21 (14-42)	5	51 (38-61)	6 (2-11)	12 (6-19)	19 (8-44)
3	43 (27-65)	2 (1-3)							
2	44 (37-51)	6 (2-9)							
1	39	5			5	48 (26-61)	4 (2-7)		
3	43 (27-65)	2 (1-3)							
2	44 (37-51)	6 (3-9)							
1	39	5			5	48 (26-61)	4 (2-7)		
6	43 (27-65)	5 (1-11)			1	55	7		
1	39	5			4	47 (26-61)	4 (3-7)		
3	39 (27-51)	5 (1-11)			3	43 (26-55)	7 (3-11)		
3	39 (37-42)	5 (1-9)			2	56 (51-61)	4 (2-6)		
1	65	3							
2	38 (37-39)	4 (3-5)			4	49 (26-61)	5 (2-7)		
4	44 (27-63)	4 (1-9)			1	49	3		

graphic findings in the three groups of below-knee amputees.

amputated, 3 of whom had undergone two or three operations on the amputation stump. The reasons for re-operation were pain and infection. One patient had tenderness on the fibular side of the stump and two had ulcers on the stump.

In the 11 patients who had the least pain in the amputation stump the mean blood flow in the stump was 1.9 ml/100 ml · min and in the intact lower leg 3.3 ml/100 ml · min. The mean blood flow in the 8 patients with moderate symptoms was 2.3 ml/100 ml · min in the amputation stump and 1.8 in the intact leg. In the 6 patients with severe pain in the stump or phantom limb the mean blood flow in the amputated leg was 2.5 and in the intact leg 2.0 ml/100 ml · min. The mean age of those with the least pain was 35 years and in those with the most pain 47 years.

In 7 patients who had no or only slight pain in the amputation stump

the mean value for the *maximum blood flow* was 9 ml/100 ml · min in the stump and 22 ml in the intact leg. In the group of 6 patients with moderate pain the corresponding values were 10 ml and 21 ml/100 ml · min respectively, and in 5 patients with severe pain 12 ml and 19 ml/100 ml · min respectively. The mean age of the 7 patients with no or only slight pain was 36 years and of the 5 patients with severe pain 51 years.

Arteriography. Arteriography was performed on 21 of the above-mentioned 25 patients. The reason that this investigation was not carried out on all patients was that two of them were too young and two refused to have it done; in three patients the contrast filling in the arteries of the amputation stump was not sufficiently good to permit evaluation of the degree of vascular richness and tortuosity. One of these latter three patients had marked vascular changes with protrusions into the lumen in the popliteal artery at the level of the knee joint. One further patient, a woman, had a low blood flow in the amputation stump, i.e. 0.8 ml/100 ml · min, and the vascular network there could not be assessed until vasodilators had been administered. The same applied to one male below-knee amputee. These two latter patients could not thus be evaluated at conventional arteriography, but this was possible after an injection of bradykinin immediately before a new arteriography.

As shown in Table 28 there was a tendency to a greater number of *spiralled arteries* in the amputation stump with increasing degrees of pain in the stump. Thus among the patients with the least pain in the amputation stump 5 had no spiralled arteries, 2 had a moderate number and none of them had an abundance, while the group of 5 patients with severe pain in the amputation stump exhibited a profusion of such arteries in the stump.

The results from the investigation of the richness of arteries in the stumps were similar to those reported above concerning spiralled arteries.

The occurrence of *spur formation* in the amputation stump showed no definite correlation to the degree of pain in the amputated leg.

No *vascular wall changes* were observed in 5 patients from the group without pain, in 3 patients from the group with moderate pain and in 3 patients from the group with severe pain. Moderate wall changes with small protrusions into the lumen of the main arteries were observed in 1 patient in the pain-free group, in 3 patients in the group with moderate pain and in 2 patients in the group with severe pain. Occlusion of the popliteal artery was found in one patient in the group without pain and in one in the group with moderate pain. The mean age was higher on an average in those patients who showed vascular changes and occlusion.

Arteriovenous anasomoses were observed in 3 of the 7 patients with no or slight pain, 2 of the 6 patients with moderate pain and 4 of the 5 patients

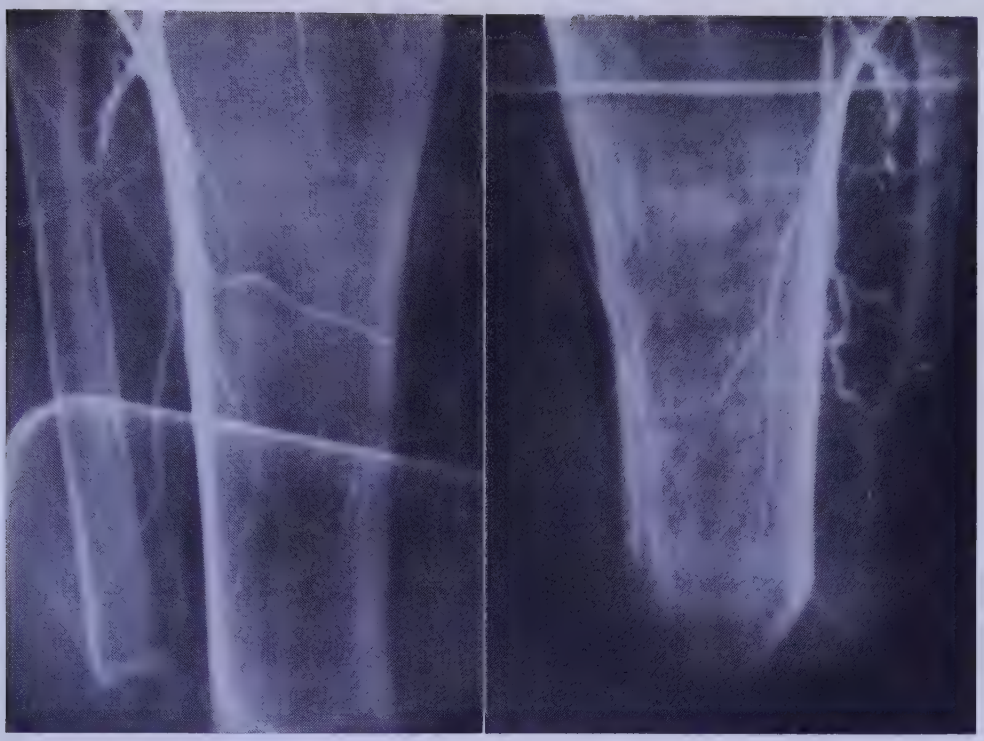


Fig. 57. Arteriographies of a male bilateral below-knee amputee. The left stump shows moderate richness of arteries and the presence of spiralled arteries, especially between the fibula and tibia. The right stump shows only a few arteries, none of which are spiralled. This patient has moderate-severe pains in the left stump, but no pains in the right.

with severe pain. There was thus a tendency to a higher incidence in the latter group.

Bilateral below-knee amputees. Both arteriography and plethysmography were performed on 3 bilateral below-knee amputees.

One of these patients was a 15-year old boy. In his left stump the resting blood flow was 3.7 ml/100 ml · min, and in the right stump 2.6 ml/100 ml · min. The blood flow during reactive hyperemia was not measured. In neither of the stumps was any increase in vascularization or any spiralled arteries observed. In the left stump a spur had formed. No vascular changes were seen, nor arteriovenous anastomoses.

The second patient was a 50-year old man. The resting blood flow in his right amputation stump was 2.8 ml/100 ml · min, and in his left stump 1.4 ml/100 ml · min. The corresponding maximum flows during reactive hyperemia were 15 ml and 12 ml/100 ml · min, respectively. Arteriography

showed an abundance of tortuous arteries and also increased vascularization in the right stump. In this amputation stump the patient suffered from moderate pain and ulcers. In the left stump the vascularization and incidence of spiralled arteries were moderate; the patient had very little pain on this side. There was no tendency to spur formation, but protrusions into the lumen of the popliteal artery were seen. No arteriovenous anastomoses were seen in either stump.

The third of these patients was a 45-year old man. The resting blood flow in his left amputation stump was 3.6 ml and in his right stump 1.4 ml/100 ml · min. The maximum flows during reactive hyperemia were the same on both sides, i.e. 12 ml/100 ml · min. In this patient arteriography showed an abundance of small spiralled arteries on the fibular side of his left amputation stump, while in the right stump there was a low number of such arteries. No wall changes were seen in the popliteal artery. A spur was present in the right stump but not in the left. Arteriovenous anastomoses had developed especially in the left stump and possibly in the right. The patient suffered from pain in the left amputation stump and for this reason had undergone several re-operations. He had never had pain in the right stump (Fig. 57).

II. Comparison between arteriographical and clinical findings.

Above-knee amputees. The results from 42 unilateral above-knee amputees and 3 bilateral above-knee amputees are reported here. Of the 42 unilateral amputees 16 had no or only slight pain, 10 had moderate pain and 16 severe pain. Table 29 shows the results from these investigations.

Of the patients who had no or only slight pain in the stump, 14 had no *spiralled arteries* and 2 a moderate occurrence of such arteries. Among the group with moderate pain 3 patients showed no spiralled arteries, 6 a moderate occurrence and 1 an abundance. Among the group with severe pain 1 patient showed no spiralled arteries, 7 a moderate occurrence and 8 an abundance.

Evaluation of *the vascular richness* in the amputation stumps gave similar results to those obtained for the incidence of spiralled arteries, a tendency to an increase being found with increasing degrees of pain.

Spur formation occurred in 7 of the 16 patients with no or only slight pain in the stump, in 7 of the 10 patients with moderate pain and in 10 of the 16 patients with severe pain. There was thus a tendency to an increased incidence of spurs with increasing degrees of pain.

No *wall changes* were seen in 12 of the 16 patients with no or slight pain

		No pain in stump or phantom limb			Moderate pain in stump or phantom limb			Severe pain in stump or phantom limb		
		No. of cases	Age at examination (years)	Time since amputation (years)	No. of cases	Age at examination (years)	Time since amputation (years)	No. of cases	Age at examination (years)	Time since amputation (years)
Presence of spiralled arteries in stump	No	14	38 (16-59)	5 (1-14)	3	38 (23-61)	8 (1-14)	1	38	9
	Moderate	2	44 (21-61)	1	6	40 (18-53)	6 (1-12)	7	44 (21-68)	22 (5-49)
	Abundant	-			1	37	2	8	48 (27-61)	8 (1-28)
Richness of arteries in stump	Few	10	37 (16-59)	6 (1-10)	4	42 (23-61)	8 (1-14)	2	53 (38-68)	29 (9-49)
	Moderate	6	40 (21-66)	3 (1-7)	5	37 (18-48)	5 (1-12)	9	45 (21-62)	16 (4-46)
	Abundant	-			1	37	2	5	45 (27-59)	5 (1-12)
Presence of spurs	Present	7	41 (17-66)	4 (1-9)	7	37 (18-53)	5 (1-12)	10	44 (21-61)	17 (4-49)
	Not present	9	36 (16-58)	5 (1-10)	3	43 (31-61)	6 (1-14)	6	50 (27-62)	10 (1-12)
Wall change in main artery	No	12	34 (16-66)	4 (1-10)	10	43 (18-61)	6 (1-4)	11	40 (21-59)	10 (1-46)
	Moderate	3	53 (45-59)	5 (4-7)	-			3	61 (61-62)	26 (24-28)
	Obliteration	1	47	14	-			3	59 (55-68)	19 (4-49)
Presence of A-V anastomoses	Present	1	22	1	-			2	52 (45-59)	11 (10-12)
	Not present	15	38 (16-66)	4 (1-10)	10	43 (18-61)	6 (1-14)	14	45 (21-61)	16 (1-49)

Table 29. The table shows the arteriographic findings in the three groups of unilateral above-knee amputees.

in the stump, in any of the 10 patients with moderate pain and in 11 of those 16 with severe pain. Vascular changes in the form of protrusions into the lumen occurred in 3 of the patients with no or slight pain and in 2 of those with severe pain. Occlusion of the superficial femoral artery was seen in one patient with no or slight pain and in 3 patients with severe pain in the stump. The patients who exhibited vascular changes or occlusion were of a higher mean age than those in whom these were completely absent (see chapter II).

In 2 of the patients with severe pain *arteriovenous anastomoses* was observed, and in 1 of the patients with no or slight pain there were signs indicating this condition. In none of the other patients was this observed.

Bilateral above-knee amputees. The three bilateral above-knee amputees showed the following results. Two of the patients belonged to the group with no pain in the amputation stump; these patients were 27 years and 32

		No pain in stump or phantom limb			Moderate pain in stump or phantom limb		
		No. of stumps	Age at examination (years)	Time since amputation (years)	No. of case	Age at examination (years)	Time since amputation (years)
No spiralled arteries present		4	30 (27-32)	4 (1-6)	2	53	17
Richness of arteries in stump	Few	3	"	"	2	"	"
	Moderate	1	"	"			
Presence of spurs	Present	3	"	"	1	"	"
	Not present	1	"	"	1	"	"
No changes of artery wall		4	"	"	2	"	"
Presence of A-V anastomoses	Not present	4	"	"	2	"	"

Table 30. The table shows the arteriographic findings in the bilateral above-knee amputees of two clinical groups.

years old. All four amputation stumps showed the complete absence of spiralled arteries, three stumps had low vascularization and one moderate vascularization. Spurs were seen in three amputation stumps. In none of the stumps were there any vascular changes, and no arteriovenous anastomoses were observed in these patients. The third bilateral above-knee amputee was a 53-year old man with moderate symptoms of pain. He showed no spiralled arteries and no increase in vascularization in the amputation stump. This patient had a spur in one stump. He showed no arterial wall changes and no arteriovenous anastomoses. The results are given in Table 30.

Below-knee amputees. The results from the comparisons between the arteriographic and clinical findings are given in Table 31. This investigation includes 47 unilateral and 6 bilateral amputees. These latter patients are shown in Table 32. Twenty-seven of the unilateral below-knee amputees had no or only slight pain in the amputation stump, 10 had moderate pain and 10 had severe pain.

Twenty of the 27 patients with no or slight pain in the amputation stump showed no *spiralled arteries*. Three of the 10 patients with moderate pain lacked spiralled arteries but in all of the patients with severe pain such arteries were found. Of these latter patients 8 had an abundance of spiralled arteries and 2 a moderate number. Thus there was a tendency to an increase in the incidence of spiralled arteries with increasing degrees of pain in the amputated leg.

The evaluation of the arterial richness in the stump as correlated with

		No pain in stump or phantom limb			Moderate pain in stump or phantom limb			Severe pain in stump or phantom limb		
		No. of cases	Age at examination (years)	Time since amputation (years)	No. of cases	Age at examination (years)	Time since amputation (years)	No. of cases	Age at examination (years)	Time since amputation (years)
Presence of spiralled arteries in stump	No	20	39 (12-64)	8 (1-32)	3	41 (25-64)	2 (1-3)			
	Moderate	6	37 (17-52)	13 (1-17)	5	48 (36-57)	6 (1-18)	2	52 (39-66)	11 (10-12)
	Abundant	1	66	37	2	40 (38-42)	8 (5-11)	8	50 (26-65)	6 (1-18)
Richness of arteries in stump	Few	21	40 (12-64)	10 (1-37)	3	41 (25-64)	2 (0-3)	-		
	Moderate	5	34 (17-52)	8 (2-19)	6	47 (36-51)	7 (1-18)	3	53 (39-66)	10 (7-12)
	Abundant	1	66	37	1	38	5	7	49 (26-65)	5 (1-18)
Presence of spurs	Present	15	40 (17-66)	12 (1-37)	6	48 (36-64)	8 (2-18)	2	58 (54-62)	13 (7-18)
	Not present	12	40 (12-64)	8 (3-20)	4	40 (25-49)	2 (1-5)	8	49 (26-66)	6 (1-12)
Wall change in main artery	No	21	36 (17-64)	7 (1-37)	6	40 (25-49)	4	5	45 (26-54)	4 (2-5)
	Moderate	4	58 (52-66)	26 (17-37)	3	48 (38-57)	11 (5-18)	5	57 (39-66)	10 (1-18)
	Obliteration	2	41 (37-51)	15 (11-19)	1	64	3	-		
Presence of A-V anastomoses	Present	5	26 (12-48)	5 (1-13)	4	41 (38-49)	5 (1-11)	4	48 (26-65)	4 (1-7)
	Not present	22	43 (15-66)	12 (1-37)	6	47 (25-64)	6 (1-18)	6	53 (39-66)	9 (2-18)

Table 31. The table shows the arteriographic findings in the unilateral below-knee amputees of three clinical groups.

the clinical findings showed similar results to that concerning spiralled arteries. Thus the degree of *arterial richness* in the amputation stump increased with increasing degrees of pain.

The incidence of *spur formation* in the amputation stumps showed no definite relationship to the degree of pain.

In 21 of the 27 patients with the smallest degree of pain, no *arterial wall changes* were found; 4 had moderate changes and 2 total occlusion of the popliteal artery. In the 10 patients with moderate pain, 6 had no arterial wall changes, 3 had moderate changes and 1 occlusion. In the group of 10 patients with severe pain in the amputated leg, 5 had no arterial wall changes while 5 showed such changes. No patient had total occlusion. The mean age was higher in the patients with vascular wall changes.

Arteriography showed the occurrence of *arteriovenous anastomoses* in 5

		No pain in stump or phantom limb			Moderate pain in stump or phantom limb		
		No. of stumps	Age at examination (years)	Time since amputation (years)	No. of cases	Age at examination (years)	Time since amputation (years)
Presence of spiralled arteries in stump	No	2	15	13			
	Moderate	5	41 (28-58)	8 (1-20)	1	43	20
	Abundant	1	50	1	3	64 (58-67)	32 (8-44)
Richness of arteries in stump	Few	4	22 (15-28)	9 (4-13)	-		
	Moderate	3	50 (43-58)	10 (1-20)	1	43	20
	Abundant	1	5	1	3	64 (58-67)	32 (8-44)
Presence of spurs	Present	3	27 (15-43)	12 (4-20)	1	67	44
	Not present	5	40 (15-58)	5 (1-13)	3	56 (43-67)	24 (8-44)
Wall change in main artery	No	5	26 (15-43)	11 (4-20)	2	55 (43-67)	32 (20-44)
	Moderate	3	53 (50-58)	3 (1-8)	2	62 (58-67)	26 (8-44)
	Obliteration	-			-		
Presence of A-V anastomoses	Present	1	43	20	3	59 (43-67)	36 (20-44)
	Not present	7	35 (15-58)	6 (1-13)	1	58	8

Table 32. The table shows the arteriographic findings in bilateral below-knee amputees.

of the patients with the smallest degree of pain, in 4 of those with moderate pain and in 4 with severe pain. This investigation thus showed a tendency to an increased incidence of arteriovenous anastomosis in the patients with moderate or severe pain in the amputation stump.

Bilateral below-knee amputees. The results from the investigations of the 6 bilateral below-knee amputees are shown in Table 32, where the number of stumps is given, since in two bilateral male below-knee amputees different degrees of pain occurred in their respective stumps. The results from the 12 amputation stumps agree with those for the unilateral below-knee amputees (Table 32).

Discussion

The clinical evaluation may obviously be subjective, and different patients tolerate their symptoms to different degrees. The groups with the smallest and greatest degrees of pain in the amputated leg are probably the most

easily assigned patients. The middle group, with moderate pain, comprises individuals whom it is more difficult to place. Such problems always occur in a clinical classification of patients whose symptoms and case history findings constitute the basis of their evaluation.

The agreement between the results from above-knee and below-knee amputees in the evaluation of the blood flow and arteriographies, and the incidence of disabling symptoms indicates, however, that the clinical evaluation has a real significance and a fair degree of reliability. The results indicate that in the amputation stumps which give the most symptoms there is a higher resting blood flow and also a higher maximum blood flow during reactive hyperemia than in the stumps in which the symptoms are least significant. This holds for both above-knee and below-knee amputees. These higher blood flows appear to be correlated to changes in the vascular anatomy in the form of an increased incidence of spiralled arteries, increased vascularization and an increase in the frequency of arteriovenous anastomoses. This latter finding was observed particularly in the investigation of below-knee stumps. In evaluating these findings comparison may be made with the results of Hulth & Högström (1961) from their investigations on the pO_2 in venous blood from amputation stumps. These authors found an increase in this value in amputation stumps.

The incidence of spur formation does not appear to have any definite relationship to the degree of symptoms. It is known, however, that in some cases exostoses may give rise to localized tenderness by their effect on the soft tissues when a prosthesis is worn and may therefore be an indication for operation. A tendency was found to an increased frequency of vascular changes with increased degrees of pain, in both above-knee and below-knee amputees. The reason for this is difficult to determine, however. The vascular changes may be regarded as arteriosclerotic even if there is no definite evidence for this view. The patients who exhibit vascular changes are of a considerably higher mean age than those without such changes. Those patients who have pain in their amputation stumps show a tendency to a somewhat higher mean age than the symptom-free patients; this may possibly be one explanation. It is thus possible that it is not the symptoms themselves that are correlated to the increased degree of arterial changes but that this finding is connected with an age factor.

Summary

Comparison between the symptoms of the amputees and the results of arteriography and blood flow measurements has shown that

1. Amputation stumps with a high degree of painful symptoms have on

an average a somewhat higher resting blood flow and maximum blood flow during reactive hyperemia than symptom-free stumps, but with individual overlap.

2. Amputation stumps which give a high degree of symptoms show a higher incidence of spiralled arteries and greater vascularization than stumps which give no symptoms.

3. There is a tendency to a greater occurrence of rapid arteriovenous communication in amputation stumps with symptoms than in those without, but with individual overlap.

4. The incidence of arteriosclerosis-like arterial changes in the amputation stumps with symptoms is fairly similar to or possibly somewhat higher than that in the stumps without symptoms.

5. The incidence of spur formation does not appear to be correlated to the degree of symptoms.

There thus seems to be some reason to assume that a change in the vascular anatomy and the blood flow in the amputation stump may be in some way connected with the aetiology of painful symptoms in the amputation stumps.

General Discussion

The group of patients has been studied mainly with regard to conditions in the amputation stump as compared with the intact leg. This series of patients agrees in many respects, for example in its absence of primary vascular disease, with the so-called 133-series described by Hanson (1964) in his study of leg amputees. This latter series consisted of patients who were less than 60 years old at the time of the investigation. The present series, however, included a somewhat larger number of patients in the age groups above 40 years. In his study Hanson discussed the reasons for amputation, the medical and social prognosis and also rehabilitation. The findings in the present investigation can probably be complemented, therefore, from a socio-medical aspect, with the results from Hanson's study.

Some reports have been made with regard to prosthetic function and the results of physiotherapy and training at The Walking School (annual reports from The Walking School 1961 and 1962). The present series of patients was also investigated with regard to their physical work capacity, which was studied by means of graded work tests with a cycle ergometer and a tread mill (Erikson, Hulth & Ström, 1962 and 1965). It was found that the physical work capacity was considerably reduced in the above-knee amputees in particular, who showed approximately 2/3 of the expected capacity in healthy persons of corresponding age and circumstances.

The aim of the present investigation was to analyse the circulatory changes in the amputation stump and their possible connection with symptoms in the form of pain in the stump, phantom pains, stump tenderness and stump ulcers. The concept of "phantom limb" is not treated, however. The theories concerning this concept were reviewed by Frederiks (1963), who pointed out that a phantom limb is experienced by practically all patients over the age of 15–20 years. Unpleasant experiences of pain, paresthesia and cold or warmth from the phantom limb are called by this author phantom limb sensations, and he considers that this concept probably requires a separate pathophysiological explanation but may also depend partly on psychological factors.

It was shown in the present investigations that the amputation stump differed from the intact leg in many respects. The course of the arteries was

changed and they were more tortuous in certain regions. In the cases in which the veins could be studied in the amputation stump these were also often found to have a markedly tortuous appearance. The arteries appeared to have some relationship with the distal bone end in the stump, especially when a spur had formed there. Simultaneous with these changes the arterial diameters were found to be decreased in comparison with the intact leg. The proportion of muscle in the amputation stump was reduced, this reduction being greater than the decrease of the entire stump volume. The tissue proportions were estimated by means of a roentgen technique, and were found to be of value in interpreting the blood flow measurements in the amputation stumps. The blood flow at rest in a number of stumps showed a tendency to be higher than in the corresponding segment of the intact leg. The maximal blood flow during reactive hyperemia was in most amputees lower in the amputated than in the intact leg.

The vascular system in the amputation stump is probably more sensitive to bradykinin than the corresponding system in the intact leg, which was shown by a comparison between stumps in which the blood flow was measured with a segmental cuff and those in which a bag cuff was used, the muscle proportion in the tissue regions enclosed by the segmental cuff being considerably greater than in those enclosed by the bag cuff. Considerably higher blood flows were recorded in the regions with high proportions of muscle tissue than in those with low. This blood flow increase in the amputation stump corresponded to a considerable increase in contrast filling at arteriography. Acetylcholine did not induce such high blood flows in the amputation stump as bradykinin, on the other hand, and on arteriography the contrast filling of the arteries in the distal stump in the region primarily supplied by the superficial femoral artery was found to be considerably decreased. The vessels of the deep femoral artery region in the above-knee amputees, were probably affected by the acetylcholine, however, and this was probably the reason for the fact that the blood flow nevertheless showed an increase compared with the initial value. The reason for the apparently reduced effect of acetylcholine in the amputation stump is not clear. It was uncertain whether histamine, ATP or noradrenaline affected the vessels of the amputation stump to a different extent from those of the intact leg.

The time course for the development of the changes observed in the amputation stump could not be studied in detail. The arterial diameters, however, appeared to show a tendency to decrease with increasing observation time. The arterial wall changes in the form of arteriosclerosis-like protrusions into the lumen appeared in some cases to occur as early as during the first observation year. The principal pattern arrangement of the

arteries and veins also appeared to take place at a fairly early stage after the amputation.

A study in amputated rabbits showed that changes in the amputation stump occurred relatively rapidly. Tortuous arteries and veins and also a spur-like formation developed in the rabbit stumps, these changes occurring as early as 3–4 weeks after the amputation (Erikson & Olerud, 1965). Spur formation appeared to have some relationship to a haematoma in the rabbit stump, this haematoma then developing into bone tissue. Simultaneous with this bone development the vascularization in the stump increased.

Changes in the degree of vascularization and the frequency of spiralled arteries in the amputation stump appear to be of some significance in the development of pain and ulcers in the stump; with these conditions there appears to be a tendency to a higher mean resting blood flow in the stump.

Possible reasons for the changes observed in the amputation stump have been discussed in the foregoing chapters. It is possible that if a series of patients were operated on under uniform conditions the analysis of the post-operative vascular behaviour might be simplified and the causative mechanisms could be studied more closely. For example no myoplastic operation, i.e. an operation in which the antagonists are sutured to one another in pairs, was performed on any of the patients in the present series. Such an operation is considered to improve the muscle function. In most of the patients in this material it is probable that the musculature was cut off at the amputation without any such measures being taken. It seems improbable, however, that any consequent muscle shortening could give rise to spiralled arteries.

No osteoplastic operation, in which the distal opening of the medullary canal is closed with periosteum or bone chips, was performed either. It must thus be expected that, as in the rabbits, a haematoma developed in the amputation stumps. The causative factors connected with the relationships demonstrated between painful amputation stumps, and increased vascularization with an increased frequency of spiralled arteries and a tendency to an increased blood blow, have been discussed previously. The circulatory changes may constitute a part of the causative mechanism, but may also be a resulting condition.

More detailed study of the tissue metabolism in the amputation stump would probably provide valuable information concerning the causative mechanisms. Histochemical investigations might also be of some value.

The amputation stumps thus showed many differences from the intact legs. The study of these changes is only at its early stages, however. Further knowledge in this field would probably be of value in the treatment and rehabilitation of these patients.

General Summary

In a series of patients with traumatic leg amputations the following observations were made:

1. In the amputation stumps the degree of vascularization, and the incidence of tortuous arteries varied, being either similar, somewhat increased or considerably increased compared with the intact leg.

2. The occurrence of a spur in the amputation stump appears to be related to the vascular system in the distal stump.

3. There was an increased occurrence of arteriosclerosis-like changes in the amputated leg but not in the intact leg in the somewhat older amputees.

4. 'Arteriovenous anastomoses' defined roentgenologically were observed to a relatively high degree in the below-knee stumps in particular.

5. The diameters of the main arteries measured on the arteriogram were smaller in all amputated legs than in the corresponding intact legs.

6. The passage of the contrast medium was considerably slower in the amputated leg than in the intact leg. The possibility of obtaing information about blood flow from the arteriograms was discussed.

7. In a number of amputation stumps, especially in patients of the age group 30–59 years, the resting blood flows were somewhat higher than in the intact leg.

8. The maximum blood flow during reactive hyperemia never reached such high values in the stump as in the intact leg.

9. The proportion of muscle in the amputation stump was lower than in the intact leg in both above-knee and below-knee amputees. Consideration was taken of the significance of the tissue proportions in interpreting the plethysmographic blood flow measurements.

10. The skin temperature was found to be an unreliable measure of the total blood flow in the stump.

11. The resistance vessels of the amputation stump appeared to be more sensitive to bradykinin, and somewhat less sensitive to acetylcholine than that of the intact leg. The sensitivity to histamine appeared to be similar in both legs.

12. Amputated legs which gave symptoms in the form of pain, phantom pains and ulcers had as a rule a higher mean resting blood flow than the

corresponding intact leg or stumps which gave no symptoms. The maximum blood flow during reactive hyperemia was somewhat higher in these stumps than in those without symptoms, but it was lower than the corresponding flow in the intact leg.

13. There was a positive correlation between the degree of pain in the amputated leg and the degree of arterial richness and the number of tortuous, so-called spiralled arteries in the stumps.

The vascular anatomy and function in many amputation stumps thus differ conslderably from those in the intact leg.

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